A DIGITAL INDICATOR DIAGRAM GENERATION SYSTEM FOR THE RICARDO E6 ENGINE

by
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A Thesis Submitted
in
Partial Fulfillment
of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Mechanical Engineering

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ROCHESTER, NEW YORK

MAY, 1987

Title of Thesis "A Digital Indicator Diagram Generation System for the Ricardo E6 Engine"

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ABSTRACT

This paper explains and evaluates an indicator diagram generation system for a single cylinder, internal combustion, research engine. The apparatus is digital and consists of a piezo-electric pressure transducer with charge amplifier, a shaft encoder, a digital oscilloscope, and a computer with printer. Motoring data provides valuable information on the performance of the system which is used in the computer software to produce results accurate to 5.4 percent. Results include the indicator diagram itself, the work produced, the horsepower, and the indicated mean effective pressure.

Included are an overview of indicator diagram theory, discussion of the apparatus, evaluation of the motoring data, and a thorough explanation of the computer software. Sample results taken while varying the spark advance of the engine compare well with those expected. Actual results are compared with those of the air standard Otto cycle, with the work of the actual cycle being 23 percent lower than that of the air standard.

The paper also includes complete instructions for operating the apparatus, providing directions for setting up and running the indicator diagram generation equipment and instructions for running the engine in spark ignition mode. Suggestions are made for further work so that the results may be compared to the fuel-air cycle.

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INTRODUCTION

This report describes and evaluates an indicator diagram generation system that has been assembled for use with the Ricardo E6 variable compression ratio research engine. An indicator diagram, the plot of cylinder pressure versus volume for an engine cycle, is a valuable tool in observation and evaluation of engine performance. The project involved the specification of movement parameters, the selection of the system components, and the interfacing, and writing of computer software to control the data acquisition and produce the final results.

The Ricardo E6 research engine is a versatile educational tool. It is a single cylinder engine that can be run in spark or compression ignition modes, using a variety of fuels. Its compression ratio can be changed while the engine is running, as can the carburetor settings and the spark timing. An indicator diagram of accuracy to at least two digits was needed to provide engine data for use in thermodynamics and other college level courses.

A computer controlled instrumentation system was specified and assembled. It consists of a flush mounted, water cooled piezo-electric pressure transducer, a shaft encoder, a digital oscilloscope, and the computer. The components were selected for their accuracy, versatility (the oscilloscope, for instance, will have many applications), and their ease of use. The software allows multiple indicator diagrams to be generated in a session and produces, in addition, an analysis of work output.

The theory behind engine evaluation will be discussed in the next section, beginning with the air standard Otto cycle. The air standard cycle is

a very simplified approximation of an actual cycle. The fuel-air cycle, a much more sophisticated and closer approximation to an actual engine cycle, is also presented theoretically, so that it may be used for comparison with experimental results after further development of the apparatus.

INDICATOR DIAGRAM THEORY

An indicator diagram is a plot of pressure versus volume of the cylinder or crank angle of an engine. From it, the work output and efficiency of an engine may be determined. These diagrams vary with the type of engine cycle (Otto, diesel, etc.) and the operating parameters such as compression ratio, richness of the mixture, etc. As such, they are used to evaluate engine performance and to investigate the effects of varying the operating parameters. In this discussion the indicator diagram for the Otto cycle (spark ignition, four stroke) will be addressed.

For the thermodynamic analysis of the cycle, a control volume must be defined. Figure 1 shows the control volume for the engine cylinder. V, p, and T are the volume, pressure, and temperature of the gas in the cylinder. $\dot{W}$, the power delivered to the driveshaft, and $\dot{Q}$, the power delievered by fuel combustion, are shown in the positive sense. The velocity vectors, $\overline{V}_1$ and $\overline{V}_2$, represent the velocity of the gas entering and leaving the manifolds.

The air standard Otto cycle, also called the constant volume air cycle, is an idealized standard to which a real Otto cycle can be compared (see Fig. 2). The idealization is based on the following assumptions (ref. 1, pg. 23):

1. The gas in the cylinder is air, and it behaves as an ideal gas.
2. All processes are reversible.
3. The Ideal Gas Law is valid for all processes.
4. Heat is added and withdrawn from the gas through the walls of the cylinder during both of the constant volume processes.

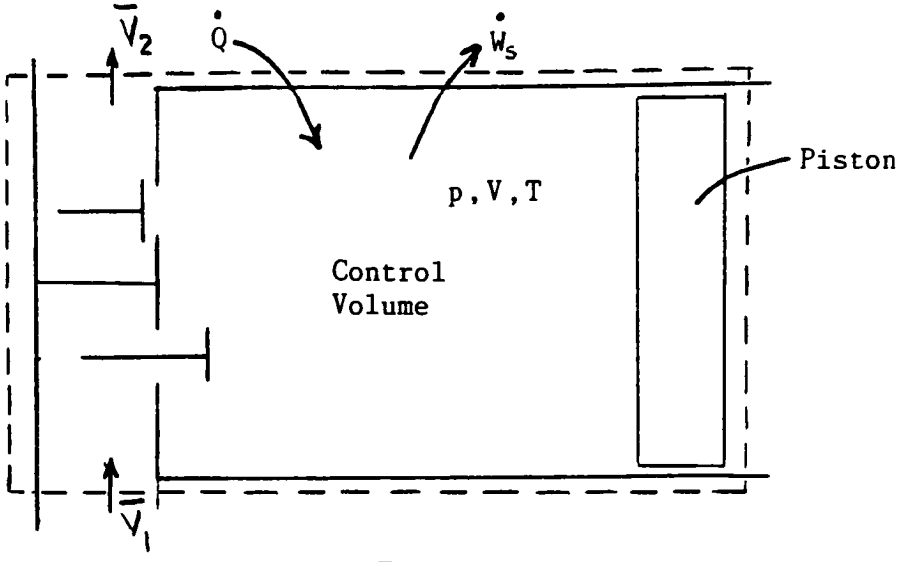


Fig.1
Control Volume for Engine Cycle
Definition of Positive Quantities

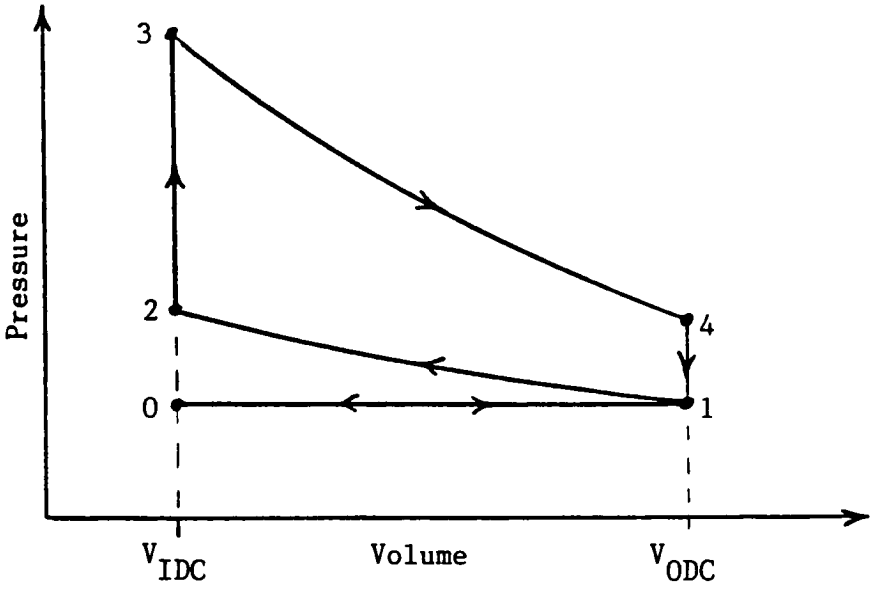


Fig.2
Indicator Diagram
for Air Standard Otto Cycle

5. No throttling of gas at the valves, i.e. gas enters and exits the control volume at ambient pressure, and velocities can be ignored.

The endpoints of the cycle on the horizontal axis of the indicator diagram in Figure 2 correspond to the cylinder volume at inner dead center (IDC) and outer dead center (ODC), the extreme points of the piston stroke. The cycle shown involves six ideal processes, four of which take place during piston strokes. These processes are as follows, with the processes involving piston movement marked by ★★:

★★ 0-1: Intake stroke. Intake valve opens at 0, the piston moves out, the intake valve closes at 1.

★★ 1-2: Piston compresses the gas.

2-3: Constant volume heat addition.

★★ 3-4: Power stroke. Gas expands.

4-1: Constant volume heat removal

★★ 1-0: Exhaust stroke. Exhaust valve opens at 1 and piston pushes gas out of cylinders.

The work associated with the indicator diagram is

$$ {}_aW_b = \int_a^b p\,d\forall \qquad [1] $$

for each process. Here, W refers to the work done by the gas on the piston. The net work is the integral around the cycle or

$$ \oint \delta W = \oint p\,d\forall \qquad [2] $$

The area under the curve for each process is, thus, the work done during that process. These areas and the net work are shown in Figure 3. It can be seen that the negative work done from 1 to 0 is cancelled out by the positive work from 0 to 1. This leaves the closed cycle 1-2-3-4-1, which can be modeled as a control mass.

The ideal processes for the air standard cycle are shown in Figure 4. Processes 1-2 and 3-4 are constant entropy (adiabatic and reversible), and 2-3 and 4-1 are constant volume. Figure 5 shows an actual Otto cycle superimposed on an air-standard cycle. The area of the power loop of the real cycle is smaller than that of the air-standard, and area of the lower loop of the real cycle represents negative work or pumping losses. As a result, we can expect the air standard cycle to have a greater net work output than can be achieved in practice.

One of the quantities that a designer is most concerned with is the thermal efficiency (η_t) of an engine, the efficiency with which the engine uses the power supplied to it. The definition of efficiency (η_t) in general is

$$\eta_t = \frac{\text{benefit}}{\text{cost}} = \frac{\oint \delta W}{{}_2Q_3} \qquad [3]$$

It can be shown (ref. 2, pg. 298) that

$$\eta_t = 1 - \frac{T_1}{T_2} = 1 - \frac{T_4}{T_3} \qquad [4]$$

This expression is concise, but the temperature in an engine cylinder is very difficult to measure. The efficiency of the air standard cycle in terms of the

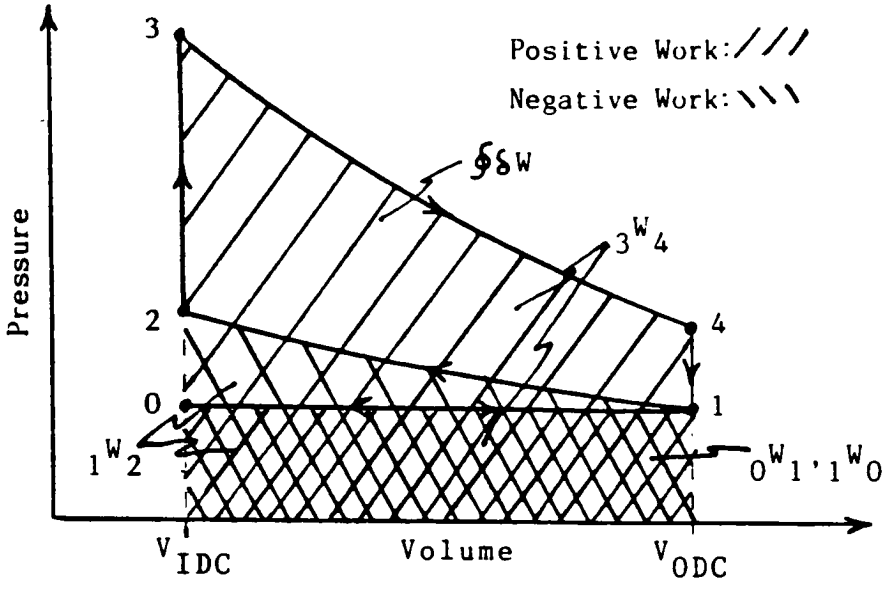


Fig.3

Work Areas for Air Standard Otto Cycle

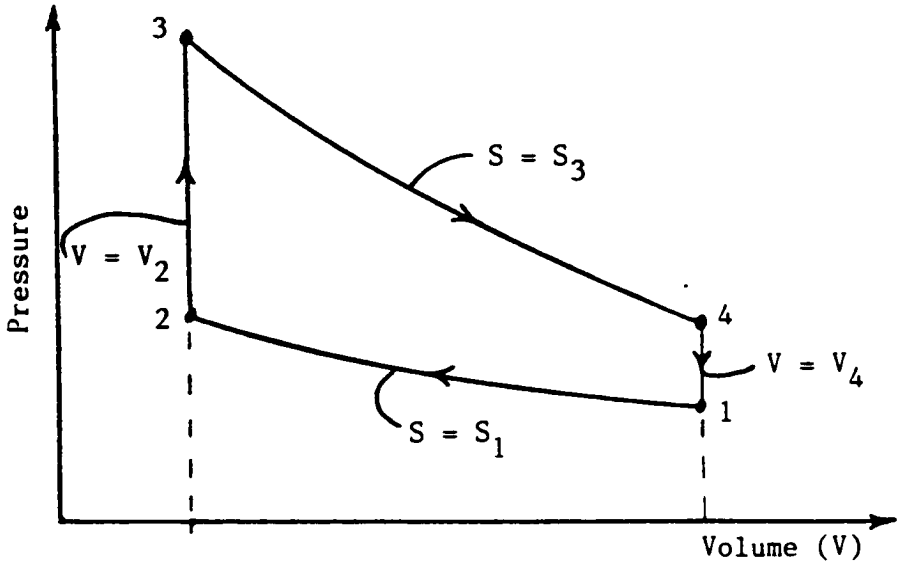


Fig.4

Non-Flow Model
of Air Standard Otto Cycle

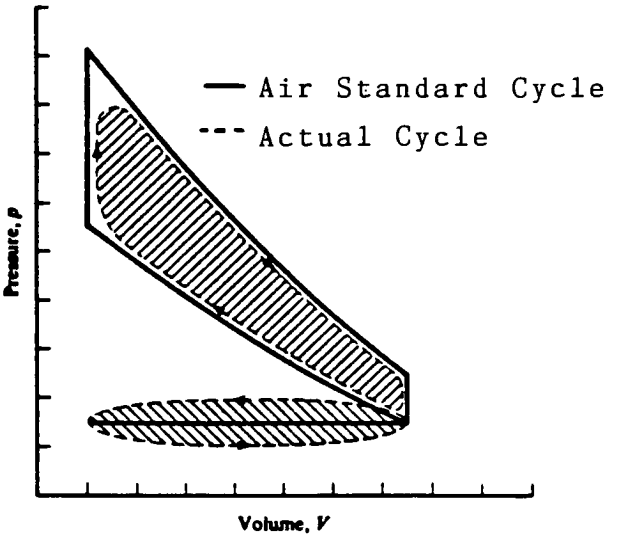


Fig.5

Schematic of Actual and
Air Standard Otto Cycles
(from ref.2,pg.308)

compression ratio, a known quantity for an engine is (see Appendix A for derivation).

$$\eta_t = 1 - \frac{1}{r_c^{\gamma - 1}} \qquad [5]$$

The above expression can be compared to the thermal efficiency found experimentally for an actual Otto cycle.

Another quantity that can be calculated with the information gained from an indicator diagram is the indicated mean effective pressure (IMEP). The IMEP represents the ratio of the net work output based on the power loop of the indicator diagram to the volume swept by the piston. Thus,

$$\text{IMEP} = \frac{\oint \delta W}{\forall_1 - \forall_2} \qquad [6]$$

The IMEP represents the theoretical pressure at which a constant pressure expansion from IDC to ODC would produce the work indicated in the diagram. Comparing engines using the IMEP instead of the net work only is a way to compensate for the size differences between engines.

The mechanical efficiency of the engine is determined from the ratio of the brake mean effective pressure (BMEP) to the IMEP. The BMEP is defined by

$$\text{BMEP} = \frac{W_s}{\forall_1 - \forall_2} \qquad [7]$$

Here, the work, W_s, is the work output to the engine shaft, usually measured by a dynamometer. The mechanical efficiency (η_m) is then calculated by

$$\eta_m = \frac{BMEP}{IMEP} \quad [8]$$

A theoretical cycle that resembles an actual engine more closely than the air-standard cycle is the fuel-air cycle. This cycle is used as a direct basis of comparison between a real cycle and an ideal one, since the working medium used is a mixture of gases closely resembling those that would be in a real engine. In the fuel-air cycle the ratio of specific heats and the specific heats of the gases change as they do in reality. Like the air standard cycle, heat is added at constant volume, but unlike the air standard, heat is taken as coming from the combustion of fuel in the cylinder. This combustion is idealized, however. The assumptions that the process is based on are as follows (ref. 1, pg. 68):

1. There is no chemical change in the fuel or air before combustion.
2. There is chemical equilibrium after combustion.
3. The gases go through adiabatic processes during compression and expansion strokes.
4. Velocities of gases are negligible in the cylinder.

When leaded gasoline is used as fuel, octene (C_8H_{18}) is used to approximate the variable mixture that actually makes up gasoline. The heat of combustion

of octene is taken to be 19,035 Btu/lbm (see ref. 1, Chs. 3 and 4 for a more complete explanation and gas tables for the fuel-air cycle).

The actual Otto cycle will now be discussed, comparing it to the fuel-air cycle. The fuel-air cycle represents the performance limit which can be approached by spark-ignition engines. Figure 6 shows how a typical engine cycle differs from the fuel-air cycle. For the comparison, the cycles are assumed to coincide as to temperature, pressure, and composition at a point such as point x in the approximate center of the compression stroke.

A fundamental difference between the two cycles is that, in the actual cycle, no process occurs at constant volume. The curves in Fig. 6 correspond very closely up to point a, since the actual compression is nearly isentropic. Ignition of the fuel occurs at point a, with the accompanying increase in pressure, and the fuel continues to burn until point b where the charge is completely burned. Points a and b are at the same piston position in a well adjusted engine. The line y-z represents an isentrope through b. The true process drops below this line because of heat loss. At point c the exhaust valve starts to open, and the pressure loss between c and 1 is due to exhaust blowdown.

Probable causes for the differences between the actual and the air-fuel cycles include the following (ref. 1, pg 108):

1. Leakage
2. Incomplete combustion
3. Progressive burning
4. Time losses (piston moving during combustion)

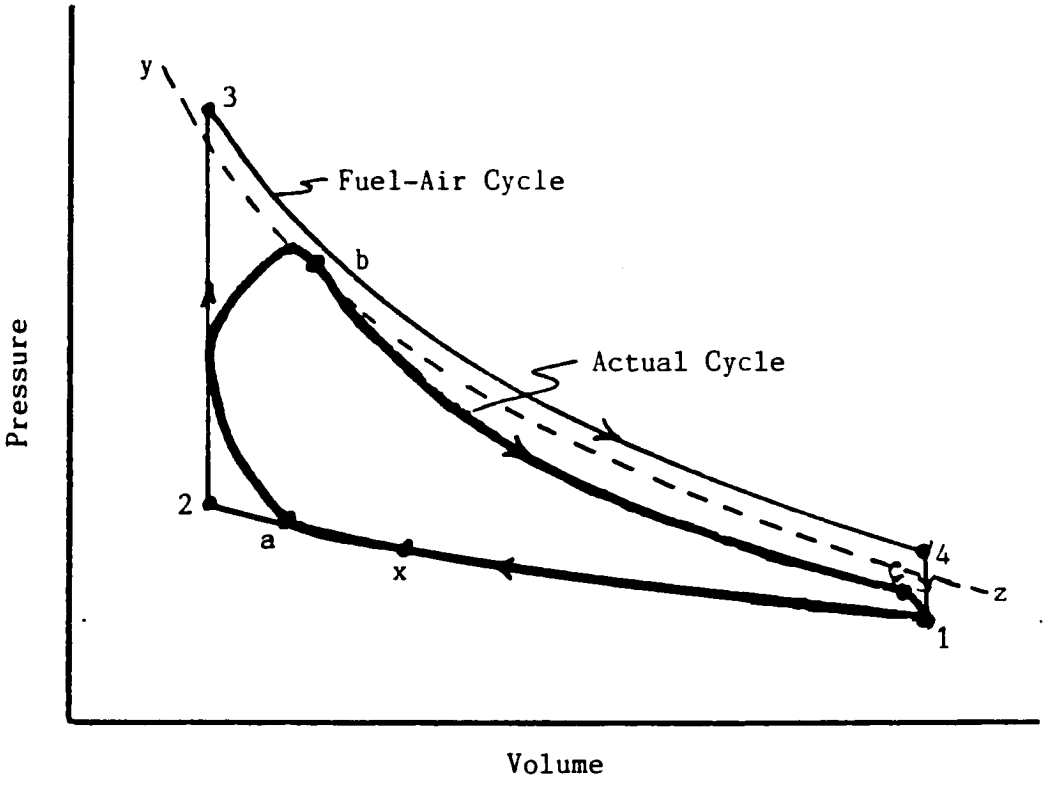


Fig. 6

Comparison of Actual and Fuel-Air Otto Cycles
(from ref.1,pg.108)

5. Heat losses
6. Blowdown and pumping losses

The contribution from leakage around the piston rings is usually insignificant except at every low engine speeds. Incomplete combustion occurs because of quenching of the flame at the cool cylinder walls. It is also known that the mixture does not reach chemical equilibrium by the time the exhaust valve opens, thus, the heat of combustion of the fuel based on calorimeter data is higher than the heat actually supplied by the charge in the cylinder.

Progressive burning is the time for the travel of the flame from the spark position through the cylinder. As mentioned above, this occurs between a and b in Fig. 6. The combustion time varies inversely with engine speed because of increased turbulence with speed (ref. 1, pg. 109), so that the crank angle occupied by combustion tends to remain constant as the piston speed varies, and the relative position of a and b does not change. Time loss occurs because the piston is moving during combustion, and the heat loss is due primarily to conduction through the cylinder wall during expansion, as stated earlier.

Blowdown and pumping losses occur when the valves are open. Figure 7 shows a detailed view of this portion of a typical indicator diagram. The momentum of the escaping gas causes the curve to fall below ambient pressure to point b. The increase in pressure from V_1 to V_2 over the exit manifold pressure, P_e, represents the pressure differential needed to push the gas from the cylinder as the piston moves from V_1 to V_2. The pressure is lower than that in the inlet manifold, P_e, to bring a new charge into the chamber. The shape of the curve in the region of IDC depends on the timing of the

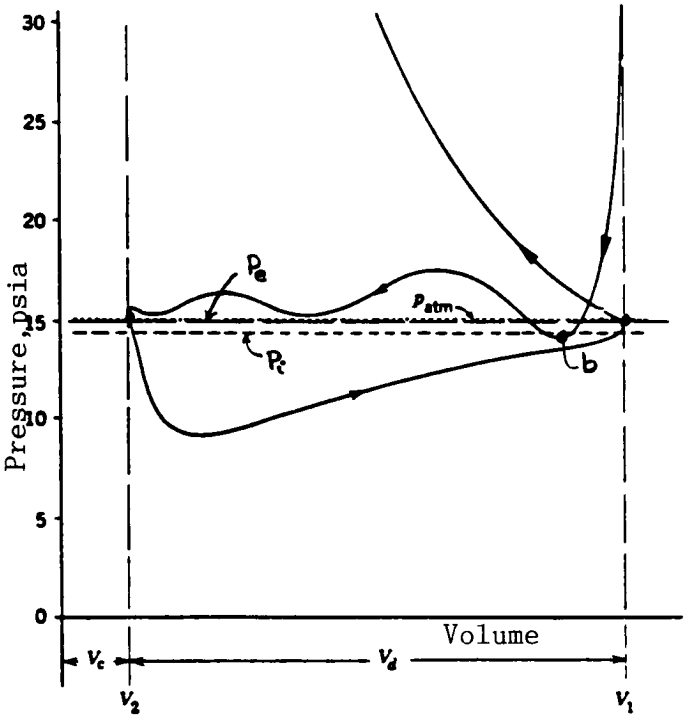
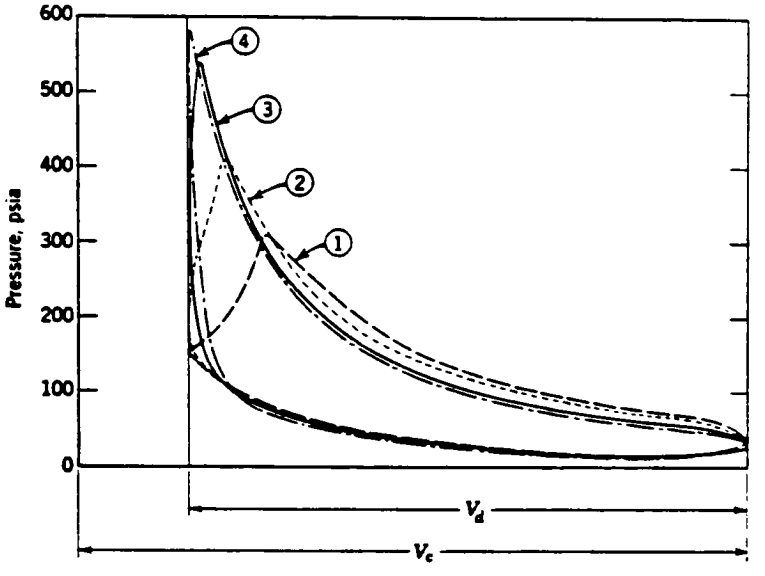


Fig.7
Schematic of Pumping Loop
of Typical Indicator Diagram
(from ref.1,pg.159)

closing of the exhaust valve and the opening of the inlet valve which occur in that area. As mentioned above, the low pressure during intake is the result of the throttling effect of the valves. The work lose due to pumping is indicated on Fig. 7 by the area of the lower loop.

Figure 8 shows the effect of variation of the spark advance on an actual indicator diagram taken from Taylor (ref. 1, pg. 128). Spark advance is the number of crank angle degrees before inner dead center that the sparkplug fires in a sparkignition engine. The general shape of the diagrams change, with the peak pressure decreasing as the spark advance decreases. The spark advance also effects the mean effective pressures, both BMEP and IMEP. Other engine operating variables such as compression ratio, fuel-air ratio, and engine speed can also be manipulated with characteristic effects on indicator diagrams (see ref. 1, pgs. 127-133). In the Results section of this paper, diagrams produced at various degrees of spark advance using the equipment assembled for the project are compared.



Curve	SA degrees	Comb Θ	Measured bmep	Measured imep	Measured η_i	Measured η_i/η_0	Motoring imep	Motoring η_i
①	0	40	72	99.0	0.252	0.73	103	0.261
②	13	40	82	109	0.278	0.82	113	0.287
③	26	38	84	109	0.278	0.82	115	0.293
④	39	39	72	99.5	0.253	0.74	103	0.263

CFR engine. $3\frac{1}{4}$ x $4\frac{1}{2}$ in; $r = 6$; $F_R = 1.13$; $\eta_0 = 0.34$; $p_i = 14.3$ psia; $p_e = 14.75$ psia; $T_i = 130°F$, 1200 rpm. (Sloan Automotive Laboratories, 11/13/47.)

Fig.8

Effect of Spark Advance on Indicator Diagram (ref.1,pg.128)

COMPONENTS OF THE MEASUREMENT SYSTEM

In order to create an indicator diagram, the instrumentation system must be able to simultaneously detect cylinder pressure and piston position. Piston position can then be converted to cylinder volume. The data must then be presented graphically. Indicator diagrams have been generated in a variety of ways in the past, and the systems used to generate diagrams vary considerably. The constraints imposed by the system and the skill of the user determine the accuracy, reliability, and, therefore, the usefulness of the diagram.

Historically, the first apparatus capable of generating an indicator diagram of sufficient accuracy to be useful was the MIT Performance Analyzer (ref. 3, pg 81-82). The MIT Performance Analyzer (similar to the Farnborough Apparatus used up to now at RIT) is a mechanical mechanism, activated by pressure, that causes a stylus to mark a card attached to a rotating cylinder. The diagram produced was actually of pressure vs. time, making the apparatus of limited value when working with many engines, and mechanical problems due to temperature effects on the hardware required frequent maintenance. Electronic cylinder performance indicators came into use in the early 1960's. These could calculate horsepower directly, but the circuit components were dedicated and had to be changed for each different transducer used. The advent of the digital computer and attendant data acquisition devices (multiple channeled A/D converters) has allowed the generation of indicator diagrams to become much more simple, flexible, and accurate. Interactive software allows the user to input parameters specific to

a run, such as the compression ratio used, and to select the output desired. A digital system is used in the present indicator diagram generation.

In order to produce an indicator diagram, four basic functional components are used. These are as follows:

1. Pressure measuring device
2. Means of tracking the cylinder volume
3. Data acquisition device
4. Data manipulation and control device

The components will be discussed separately in the following sections.

Pressure Measurement

The device used to measure engine pressure must be able to operate in the desired pressure range and to withstand severe temperature and pressure variations in the engine cylinder while giving reliable output with acceptable sensitivity. The pressure transducer used in the system here is a flush-mounted, water cooled piezo-electric pressure transducer made by Kistler Instrument Co. This type of piezo-electric transducer design is considered to be the most satisfactory for measuring pressure in an internal combustion engine (ref. 3). Being flush-mounted, there is no connecting passage between the pressure to be measured in the engine cylinder and the transducer diaphragm. Previous designs for mounting the transducer used a connecting passage in the transducer fitting between the transducer itself and the opening to the cylinder to isolate the transducer from the severe conditions in the engine cylinder. The new generation flush mounted pressure transducers

are cooled by water flowing around the piezo-electric crystals. This configuration avoids the problems of damping, phase shift, and possible ringing and attenuation of pressure input due to a connecting passage (refs. 4, 5, 6,). Temperature variation causes changes in the transducer output, called "thermal drift", due to thermal strain of the transducer diaphragm and other components. Thermal drift is kept to a minimum in the Kistler model 7061 by water cooling it.

Fig. 9 shows the water cooling system designed for the pressure transducer in this application. The system circulates distilled water from the lower reservoir, via the pump, to the upper reservoir, and it is gravity fed through the pressure transducer to the lower reservoir. Two reservoirs are used in order to isolate the pump from the transducer so that any pump vibration will not interfere with the transducer readings. The pump is a Tuthill gear pump (model B9421) which has a low flowrate of about 18 gallons/hour, which is higher than the flowrate through the transducer of about 8 gallons/hour. The overflow line is, therefore, necessary so that the upper reservoir does not overflow, and also to maintain constant pressure head level, at the level of the intake to the overflow line. The ball valve is used to prevent the upper reservoir from draining, causing the lower reservoir to overflow. The system is, thus, self-regulating, and does not need to be monitored once it is set up and running.

The specifications of the Kistler 7061 pressure transducer are given in Table 1. The 7061 has a sensitivity of 5.27 pC/psi in the 0-20 bar range. This is high compared to many such transducers which is very desirable. For instance the piezoelectric transducer previously used with the Ricardo engine

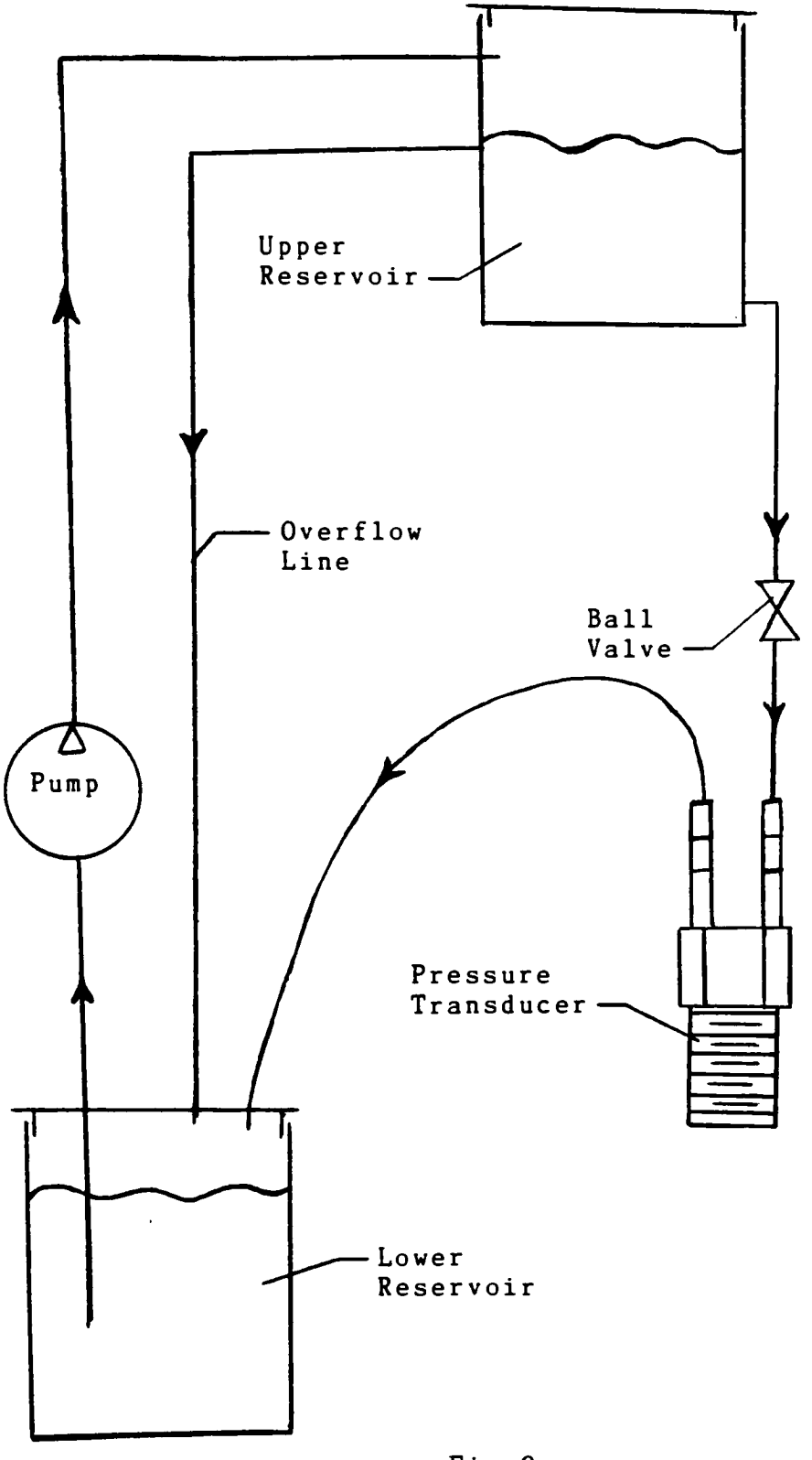


Fig.9

Cooling Water System for Pressure Transducer

Table 1

Technical Data
for Kistler Model 7061 Pressure Transducer

Range	bar	0 . 200
Calibrated partial range	bar	0 20
	bar	0 2
Overload	bar	250
Sensitivity	pC/bar	~−80
Natural frequency	kHz	>45
Linearity (for all ranges)	% FSO	≤±0 8
Hysteresis (for all ranges)	% FSO	≤0.5
Acceleration sensitivity		
without cooling	bar/*g*	<0 002
with cooling	bar/*g*	<0.004
Operating temperature range		
(without cooling)	°C	−196 350
Thermal sensitivity shift		
20 ... 100°C	%	≤±1
20 .. 350°C	%	≤±3.5
200±50°C	%	~±1
Transient temperature error	bar	~0 4
(Propane flame intermittent on front. 10 Hz)		
Insulation at 20 °C	Ω	≥10¹³
Shock resistance	*g*	2000
Tightening torque	Nm	25
Cooling water pressure	bar	≤6
Capacitance	pF	10
Mass	g	30
Plug, ceramic insulator	Type	10-32 UNF

which had a sensitivity of 1.03 pC/psi. The natural frequency of the transducer must be considered for the application. The rule of thumb used for relating the instrument's natural frequency to the frequency of the input is that, the natural frequency should be at least twice the frequency of the input. This typically guarantees a constant relationship between input and output. The 7061 has a natural frequency of more than 45 kHz. This is well above the natural frequency required by this application, since the maximum freqeuncy of the input is only 25 Hz at 3,000 rpm. The Kistler 7061 is specifically designed for use in engine testing in both spark and compression ignition modes, and can withstand the temperatures and pressures tpyically encountered. The Ricardo engine can be run in either mode while varying other operation parameters, so a transducer that can handle even the high pressures and temperatures of comparison ignition running is necessary. Also, note the low acceleration sensitivity of the transducer that prevents interference from engine vibration. Thus, the Kistler 7061 transducer was chosen for its high sensitivity, flush-mounted configuration and because it is designed specifically for service in engines.

The pressure transducer itself is only part of the pressure measurement system. The signal from the transducer must be input to a charge amplifier which converts the current output by the piezo-electric crystals into voltage. The charge amplifier is set to the transducer sensitivity (pC/psi) and the desired range (Volts/psi). The time constant of the pressure measurement system can be controlled using the charge amplifier storage time constant. The storage time constant is actually the RC time constant of the feedback circuit in the charge amplifier. The TIME CONSTANT switch selects the

feedback resistance, and the RANGE selects the feedback capacitance. It is important to select an appropriate pressure system time constant so that the output of the system tracks the input correctly. The electrical leads make up the remainder of the pressure measurement system.

The entire system must be considered when evaluating the output. The signal from the system dies out according to a time constant, which results from the effective resistance and capacitance of the circuit. The time constant must be adjusted to be as large as possible so that the output signal stays with the input level without dying out, but it must not be so large that drifting occurs. As mentioned above, the time constant can be regulated using the charge amplifier, and should be checked and adjusted at the beginning of each run as explained in the manual accompanying the charge amplifier and the appendix on setting up the system.

Volume Measurement

Cylinder volume measurement is done with the use of a shaft encoder which tracks the crank angle of the engine power shaft. If the dimensions of the cylinder and rod linkage are known, then the cylinder volume can be calculated from the crank angle.

In many modern indicator diagram generating systems, the shaft encoder delivers a pulse at each degree of crank angle and a zero pulse when the piston is at IDC (zero degrees crank angle). The Ricardo engine has a massive flywheel on the drive shaft, so that the angular velocity of the drive shaft can be assumed to be constant when the engine is operated at steady

state. Thus, a shaft encoder signal at zero degrees of crank angle is sufficient for calculating piston position.

The shaft encoder used here (Sequential Information Systems, Inc. model 25GN) delivers a square wave with an amplitude of about 5 Volts once per revolution. The wave is first used to determine the rate of rotation of the (revolutions per second) of the drive shaft. The entire cycle, which takes place in two revolutions, can then be captured by recording the pressure in the cylinder for two revolutions after triggering off the shaft encoder signal.

The critical factors considered in choosing a shaft encoder for engine applications are the maximum slew speed (maximum rpm), the rise time of the signal, and the construction of the device. The 25GN has a maximum slew speed of 3,000 rpm which is the maximum recommended rpm of the Ricardo engine. The rise time of the signal is 0.15 msec., for a maximum output of about 5 Volts, was measured. This means that the trigger lags zero degrees of crank angle by 0.86 degrees at 3,000 rpm and by 0.34 degrees at 1,200 rpm (see Appendix B for calculations). The lag results from the oscilloscope trigger level being set at 1.6 Volts for the shaft encoder. The trigger level was set at this level by empirically trying various levels that would consistently trigger the scope from the rising edge of the encoder signal. It was found that lower trigger levels did not trigger the scope reliably. The variation of trigger lag with rpm should be compensated for by the computer software. The 25GN is designed for use in dirty environments, since it has a sealed shaft. It is made for use in industrial applications and subjected to vibration as it would be when mounted in an engine.

The shaft encoder signal is fed directly to Channel 1 of the oscilloscope, where it is used to trigger the scope and measure engine rpm.

Data Acquisition Device

A Tektronix Digital Oscilloscope (model 2430) is used to acquire and digitize the data in this system. The two channel oscilloscope can be programmed by a computer through the interface bus, and all the front panel settings (sec./div., Volts/div., trigger settings, etc.) can be controlled by the computer. The data can be downloaded to a computer for processing. The sampling rate (number of readings acquired per second) of the oscilloscope is an important parameter to be considered. The sampling rate, necessary to acquire one data point per crank angle degree, is 18 kHz at 3,000 rpm. The scope acquires 1024 data points of 8 bits each per waveform at a maximum sampling rate of 100 MHz. This means that the sampling rate is more than adequate for the application and the data is good to three significant digits. The oscilloscope can average the data over a preset number of waveforms, which is important in engine applications, since there is pressure variation between cycles (ref. 7, pg 3). The waveform can also be viewed on the scope screen, which is useful during initial setup of the system and for monitoring the progress of the data acquisition.

Computer

The data manipulation and control device consists of a Hewlett-Packard 9826 Desktop computer and the program, "IND". As mentioned above, the computer is designed to communicate with other devices through its interface bus. The program contains these communications in high level commands in the "OUTPUT" and "ENTER" statements it contains. Besides controlling the information flow between the computer and the oscilloscope, the program must also acquire information from the user, handle and store the data, mathematically manipulate the data, and present the results of the run. The program was written to perform these tasks in an efficient and user friendly manner. Highlights of the program will now be presented with a brief overview of its structure.

When the program runs, the first task it performs is to print some basic equipment setup messages on the screen, to remind the user to connect the transducers to the correct oscilloscope channels, apply an excitation voltage to the shaft encoder, etc. Then the user is prompted to input the change amplifier range setting, the number of engine cycles to be averaged over, and the angular offset between the crank angle at which the shaft encoder output goes high and zero degrees (inner dead center). These quantitites are then used to calculate cylinder pressure, determine an averaged and, therefore, more accurate result, and to correct for shaft encoder misalignment, respectively. The scope settings are then initialized to their power-up state by a single output statement so that they are known at the beginning of each run.

Since the maximum resolution of the scope is 256 increments vertically and 1024 increments horizontally, the volts/div. and seconds/div. settings must be adjusted so that an engine cycle occupies as much of the available resolution as possible without running off the scale. The program adjusts the scope settings as follows. The trigger source for the scope is the positive slope of the zero pulse of the shaft encoder, and the horizontal scope setting is adjusted so that three of these leading edges are captured on the screen. One complete engine cycle is thus captured and occupies as much of the screen as possible. The vertical settings (Volts/div.) is then adjusted in a similar manner, but by looking at the input from the pressure transducer. The scope is now ready to acquire data, averaging over the desired number of waveforms.

After the waveform has been acquired and averaged, the computer converts the raw data to units of pressure, volume, and crank angle. The phasing between pressure and crank angle (and volume) adjustment is made based on the shaft encoder alignment input by the user and motoring results (see Motoring section for explanation). Calculations use the trapezoid method of numerical integration to determine the engine work. The results for the run appear on the computer screen and hard copies can be produced if desired. The results include the following:

Plot of cylinder pressure vs. volume

Listing of modified data: pressure, volume, crank angle

List of analytical results, including:

Gross work output

Valve losses

Net work output

Indicated horsepower

Indicated mean effective pressure

For a detailed description of the computer program and a thorough discussion of the rationale behind it, see Computer Software, Appendix C. Figure 10 shows the basic setup of the equipment schematically. Instructions for setting up and running the indicator diagram generation system are contained in Appendices D and E, respectively.

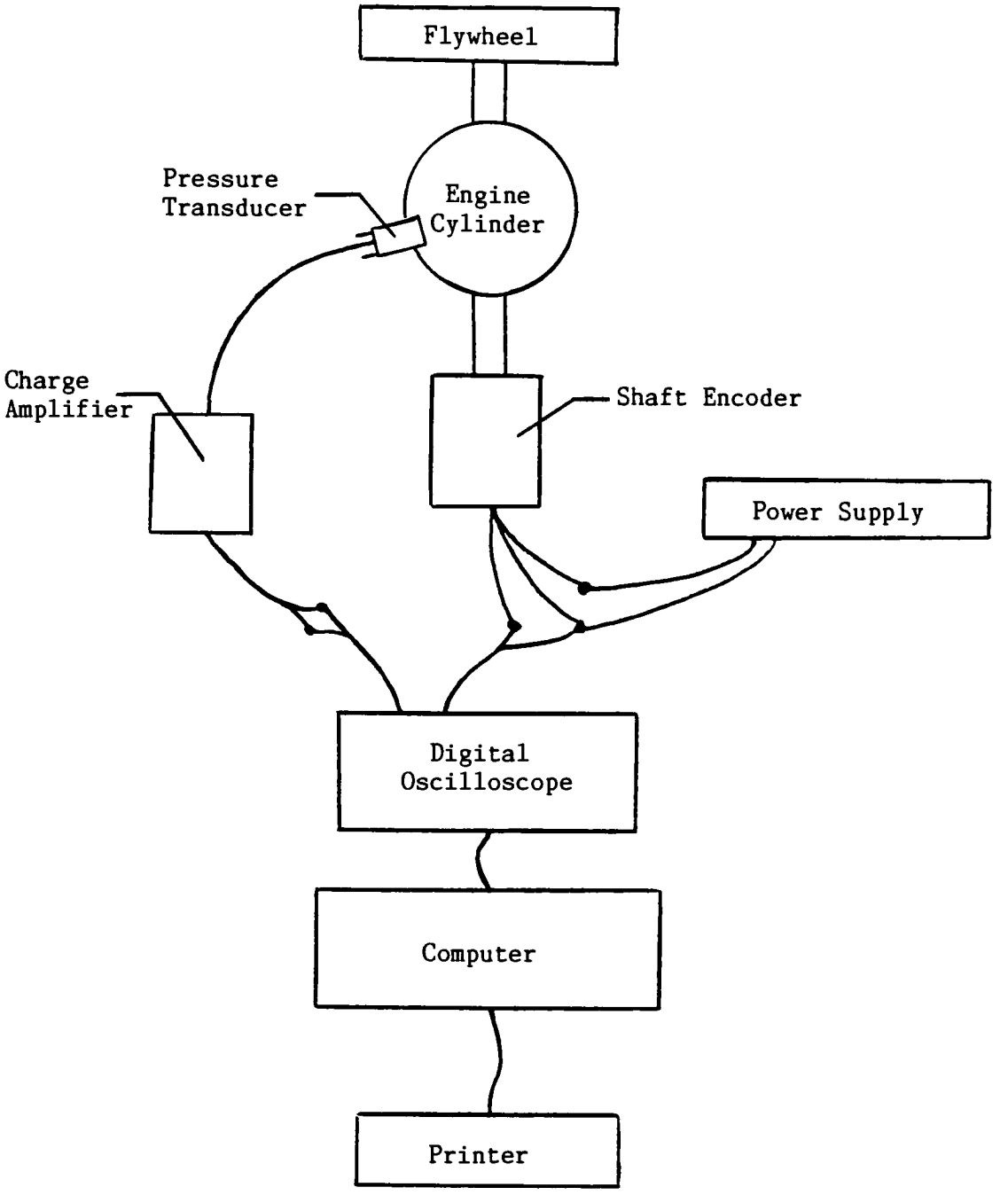


Fig.10
Schematic of Engine and Indicator Diagram
Generating Equipment

EVALUATION OF MOTORING DATA

Before generating data while the engine is firing, the motoring data, taken while the dynamometer is turning the engine over, should be evaluated to check some key system variables (ref. 7 pp. 5-7). Motoring data is useful for several reasons. First, there is little variation between cycles in motoring data and so this data can yield information about the accuracy and reliability of the test setup. Motoring data is also not affected by various combustion-introduced phenomena such as inhomogeneities and high rates of heat transfer. The motoring data can be used to check the following system variables:

Qualitative check of pumping loop pressure

Phasing, scaling and transducer performance from logarithmic p-V diagram

Phasing of pressure with respect to volume

Some methods of investigating the motoring data to check these quantities is discussed below (see Lancaster et al., ref. 7, for further information).

Qualitative Check of Pumping Loop Pressure

The pumping loop of the motoring data can serve as a check of the reference pressure value. The reference pressure is usually the value assigned to the pressure in the engine manifolds, and is equal to the pressure in the cylinder at a specific point in the cycle. The exhaust stroke of the pumping loop should contain pressures that are mainly above the reference pressure, and the intake stroke should take place below the reference pressure. If the pressures in the pumping loop do not meet these criteria, the reference pressure assignment is incorrect.

Checks from the Logarithmic p-V Diagram

The logarithmic p-V diagram from motoring data for the compression stroke can yield a wealth of insight into the validity of the system variable assignments. The portion of the indicator diagram data between the closing of the intake valve and just prior to the IDC can be approximated by a polytropic process, where:

$$_{p}V^{n} = \text{constant} \qquad [9]$$

The above function, when plotted on a logP-logV diagram, is a straight line with a slope of -n. Lancaster et al. (ref. 7, pg. 6) state that, when an erroneous reference pressure is assigned, the initial portion of the log-log plot shows a curvature, and the latter portion of the plot becomes curved when an incorrect clearance volume is assigned. The central portion of the log p-V compression

stroke plot can be curved if the time constant of the pressure system is too low, allowing decay of the response.

The value of n from the slope of the log-log plot should fall between 1.24 and 1.35, depending on the engine speed and other factors (ref. 7, pg. 7). Deviations from this range can be caused by an error in scaling or in the calibration or performance of the transducer system.

Phasing of Pressure With Respect to Volume

The phasing of pressure with respect to volume can be checked by looking at the data points taken near the region of peak pressure. When these data points are plotted on pressure vs. crank angle, the maximum pressure should occur just before IDC. The maximum would occur before rather than at IDC because of irreversibilities due primarily to heat transfer. Peak pressure after IDC indicates that the pressure is retarded with respect to volume, and peak pressure more than two degrees before IDC means that the pressure is probably advanced.

The results obtained while motoring the engine were evaluated according to the criteria above. The pumping loop pressure is considered first. The exhaust stroke pressure was consistently higher than the assigned reference pressure of 14.7 psia. The intake stroke pressures were lower than the reference pressure (at ODC after the intake stroke) only after about 90 degrees crank angle (see Fig.11). It would be expected that the intake pressure would fall below 14.7 psia before 90°, but the determination of the

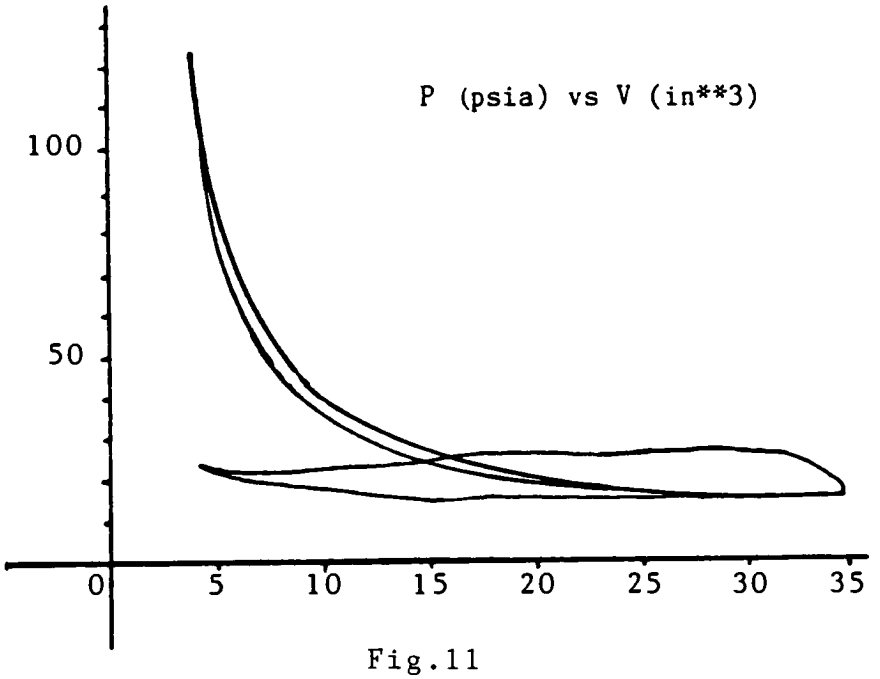


Fig.11

Indicator Diagram
Engine Motored at 230 rpm
(Actual Results)

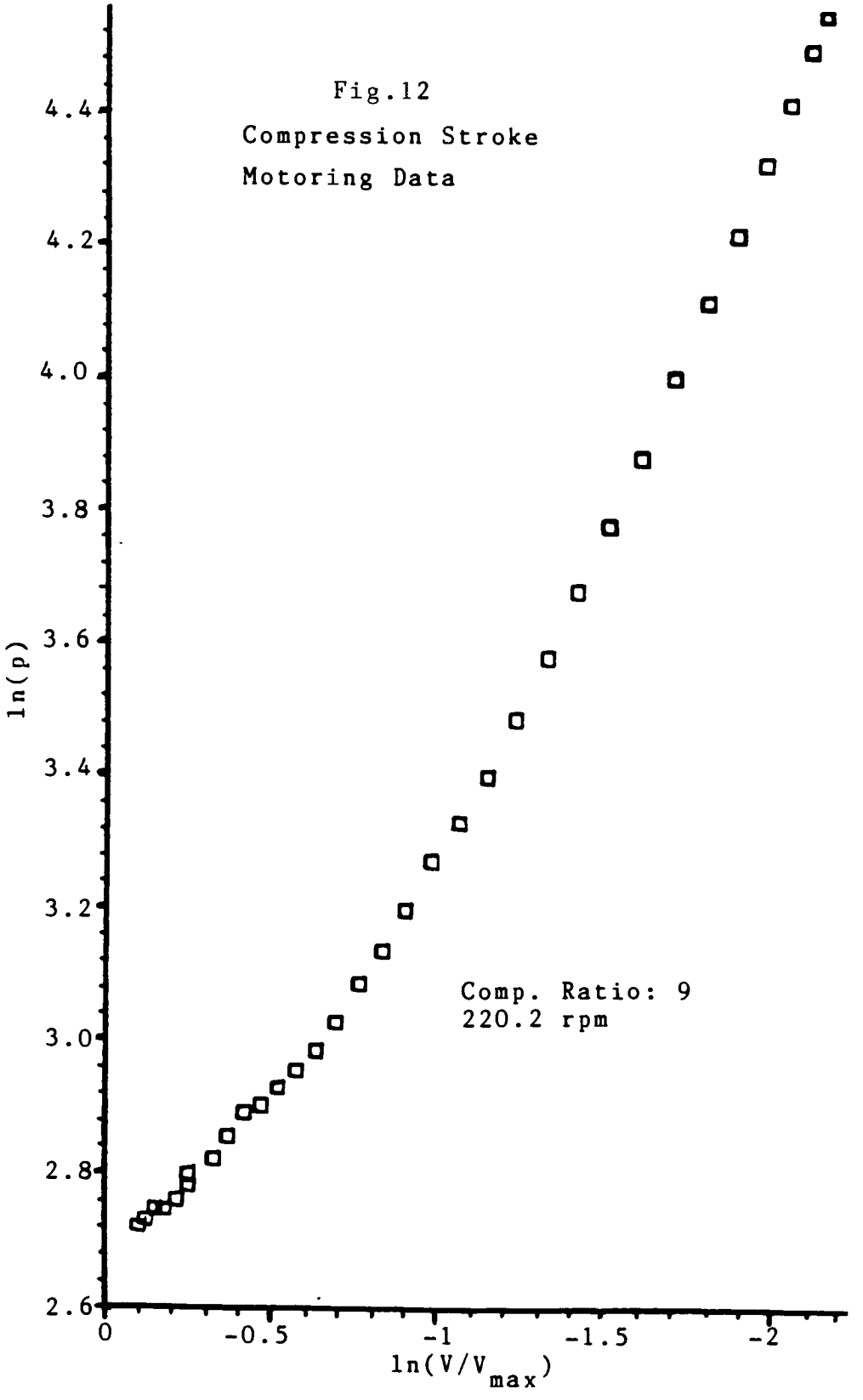
actual manifold pressure will be left for further work on this system. The value of the reference pressure does not affect the principal values, IMEP and Ihp determined from an indicator diagram.

Investigation of the logP-logV plot (Fig. 12) of the compression stroke shows that there is a curvature during the initial part of the stroke. This, again indicates that the reference pressure is suspect. The slope of the plot is -1.02, which is lower than expected. This may be due to the relatively low compression ratio used and the low engine speed.

The aspect of the motoring data that was given particular attention in this project is the phasing between pressure and crank angle data. The phasing was thought to be crucial since it has a profound effect on the indicator program produced. Phasing problems were anticipated because of the difficulty in aligning the shaft of the shaft encoder and the crank shaft, as well as the presence of a flexible coupling between the two shafts. The flexible coupling contains a rubber spider which would most likely compress proportionally with the engine speed, causing shaft encoder data to lag pressure data increasingly with rpm.

An empirical investigation of the relation between angle of peak pressure and engine speed while motoring the engine was made. The operating conditions were compression ratio of 9.0, and the shaft encoder output going high at 358 degrees as measured on the flywheel. The engine speed was varied between 202 and 2,703 rpm, with data taken while the engine speed was being increased and then decreased. Figure 13 shows the results. The vertical axis represents the difference between the theoretically correct angle of maximum pressure, 359 degrees or 1 degree before IDC, and

Fig.12
Compression Stroke
Motoring Data



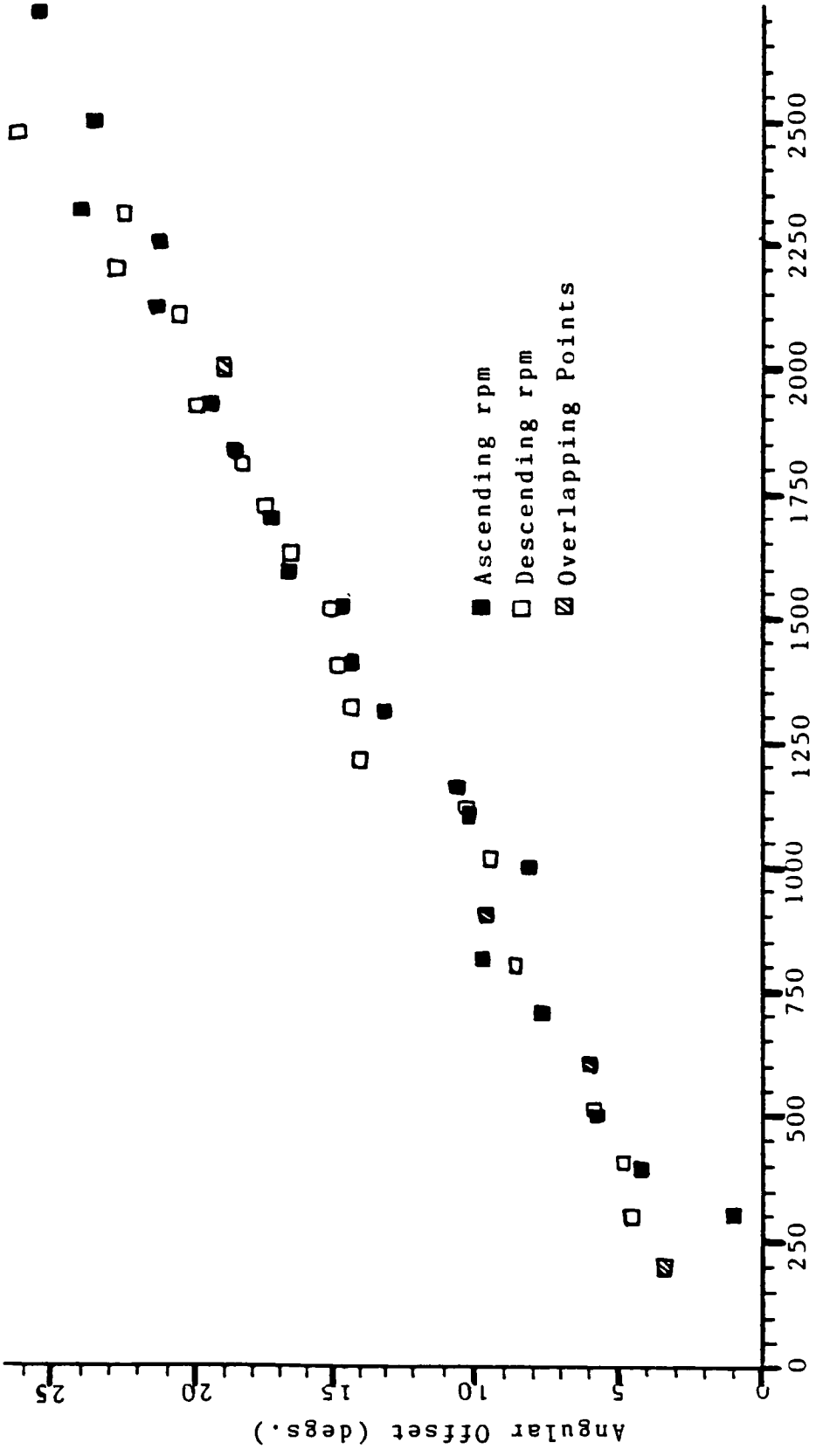


Fig.13

Variation of Angular Offset of Peak Pressure Data with RPM
(from Motoring Data)

the measured angle of maximum pressure. It can be seen that the pressure output lags the shaft encoder output increasingly with rpm. The data taken while increasing the rpm is interspersed with that taken while decreasing rpm, and the plot is fairly linear. A least square fitted line through the results yields an equation relating crank angle to rpm to correct the phase change, as follows:

$$\Delta\theta = 0.001\,(\text{rpm}) + 0.761 \pm 2.727 \qquad [10]$$

where the error is based on three standard deviations. The raw data is contained in Appendix F. It should be noted that, if the flexible coupling alone were responsible for phase change with rpm, the pressure output would be expected to lead the encoder output increasingly with rpm. However, the results are opposite to this expectation. The results point to a constant time lag between pressure and encoder output. Compression of the coupling spider with rpm would counteract this effect, but the relation would also be linear within a certain range. The net affect of these two phenomena would be a linear relationship between phase shift and engine speed, which is reflected in the data.

In conclusion, the proper phasing of pressure and crank angle data was an important result of the analysis of motoring data. The relation between phase offset and rpm resulting from the data was used in the computer software to correct for the phenomenon.

FIRING RESULTS

The firing results are presented here in two contexts so that they may be considered with respect to expected results. First, a typical set of results is compared to those calculated for an air standard cycle. Secondly, firing results, taken while the spark advance was varied from 20 degrees to 45 degrees, are presented.

During that data gathering runs, the main engine operating variables were held constant. While obtaining all results, the compression ratio was maintained at 9 and the carburetor settings were fixed. The dynamometer settings were also held constant, with the field voltage at 40 V. The engine oil temperature was about 50°C, and the inlet and outlet engine jacket cooling water temperatures were maintained at a temperature of 53°C. See Appendices G and H for data and calculations for this section.

Figure 14 compares the measured and air standard power loops. The measured data was taken with the spark advance set at 20 degrees. The peak pressure of the real cycle is much lower than and occurs later than that of the air standard cycle. This is to be expected. Comparing Fig. 14 with Fig. 5 reveals that, when comparing the experimental cycle with an air standard cycle, the measured compression stroke process line actually falls below the air standard compression stroke line, whereas Fig. 5 indicates that the real compression stroke lies below the air standard. The experimental results agree with theory because the air standard compression stroke is computed based on constant entropy while compressing air, that has a ratio of specific heats of 1.4. In the real cycle, there is a mixture of air and fuel (say, octene)

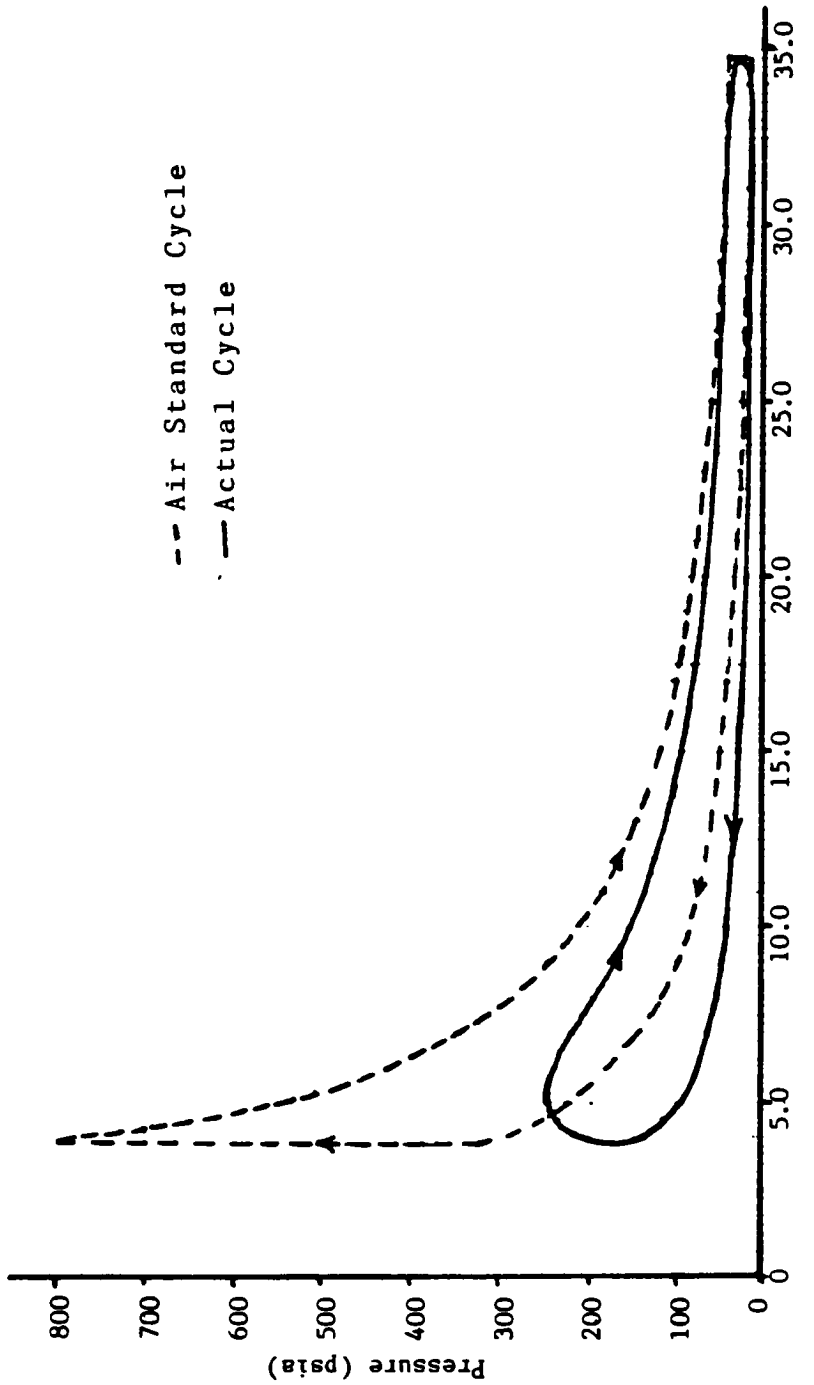


Fig.14

Comparison of Actual and Air Standard Power Loops

where octene has a ratio of specific heats of about 1.05 (Ref. 1, pg 46). This would serve to lower the value of γ of the charge in the cylinder of a real cycle to between 1.05 and 1.4, thus causing the real process curve to fall below that of the air standard curve. Another factor that contributes to the relative position of the compression curves is the assumption of the air-standard cycle that compression and expansion are constant entropy. This, of course, is not so and the real compression curve would be expected to fall below the constant entropy curve even for a cylinder charge consisting entirely of air.

Because of the relative displacement of the measured and air standard curves in Fig. 14, it is necessary to analyze the actual and air-standard results to compare the work outputs. Table 2 shows that the real work output is 23% lower than that of the air standard cycle. Many factors contribute to this lower work output, including the air-standard cycle, assumptions of constant entropy in compression and expansion strokes, and complete combustion of fuel at constant volume. As expected, the IMEP and thermal efficiency values are also lower for the real cycle.

The following portion presents results obtained while varying an engine operating condition. The operating condition that was varied was the spark advance angle since it has a very noticeable effect on the shape of the indicator diagram, the ihp, and the IMEP (refer to Fig. 8).

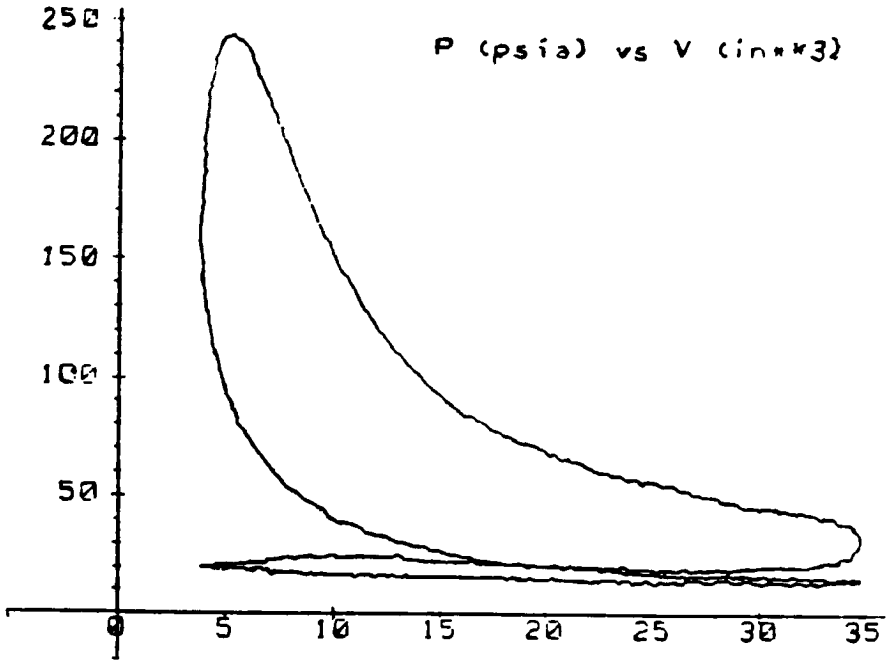
Figure 15 a and b, the indicator diagrams produced at 20 degrees and 40 degrees spark advance, respectively, show the general shape changes that result. The maximum pressure occurs closer to IDC as spark advance increases, and the power loop is more "squat" in shape at the smaller spark advance angle (20 degrees). Table 3 presents the results of varying the spark

Table 2

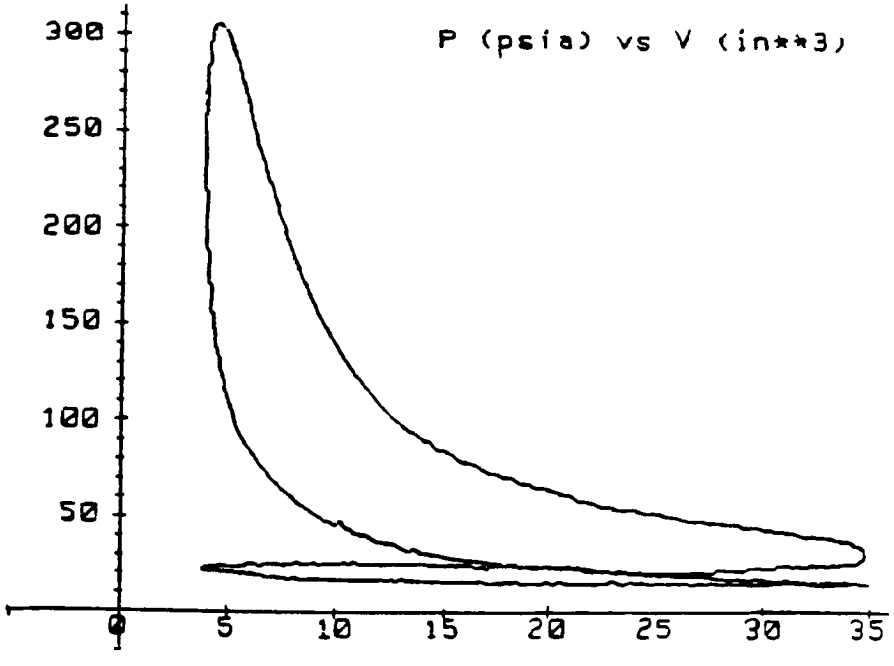
Comparison of Actual and Air Standard Cycle Results

Cycle	Work Output (ft.lb)	imep (psia)	Thermal Efficiency (η_t)
Actual	172 *	66.6	44.8 *
Air Standard	223	86.8	58.5

*power loop only



a. 20 Degree Spark Advance



b. 40 Degree Spark Advance

Fig.15

Indicator Diagrams Taken at
Two Spark Advance Settings
(Actual Results)

Table 3

Firing Results Varying Spark Advance

Spark Advance (deg.)	rpm	imep (psia)	ihp	η_m	Max Pressure (psia)	Angle of Max Pres. (deg.)
20	1360	66.6	3.22	64.0	245	25.4
25	1380	66.2	3.23	64.1	260	21.6
30	1410	66.4	3.27	63.9	268	18.7
35	1400	63.0	3.05	66.9	292	17.8
40	1400	60.8	2.91	66.3	306	16.9
45	1380	64.7	3.15	69.2	341	15.0

advance. The indicated results, IMEP and ihp, are good to about 5.7% and 5.4% respectively (see Appendix H), which are, except for the results at 45 degrees, in line with those presented in Fig. 8. From Table 3, the IMEP is highest at 20 degrees, while it is highest between 13 and 26 degrees according to Taylor's results. The two results are compatible, considering the differences in operating conditions (compression ratio, rpm, etc.). The ihp results from Table 2 show a maximum at 30 degrees, due to the higher engine speed at which that data was taken. The maximum pressure is higher at greater spark advance, and the angle of maximum pressure is smaller at larger spark advance, which are also results to be expected.

Generally, the results obtained with varying the spark advance are in good agreement with those obtained by Taylor. The complete results from firing the engine with the spark advance at 20 degrees are contained in Appendix I.

CONCLUSIONS AND RECOMMENDATIONS

As a result of this project, it is now possible to produce an indicator diagram and generate related data for the Recardo E6 Research Engine run in the spark ignition mode. The basic equipment used is a water cooled piezoelectric pressure transducer and peripherals, a shaft encoder, digital oscilloscope, and a desktop computer. Computer software developed for this system is interactive and user friendly. It is designed to achieve maximum resolution of the data, and it produces work results accurate to about 5.4%.

Preliminary evaluation of motoring data revealed that there was a phasing problem between pressure and volume data. The phase changed linearly in direct proportion to the engine speed, and the problem was corrected to within one degree of crank angle by correcting it in the computer software. Further investigation of motoring data, the log-log plot of p-V data, and analysis of the pumping loop, indicates that there may be a problem with assignment of a reference pressure. This aspect is not considered important here, since it does not affect the results obtained from the indicator diagram (work, power, etc.). Obtaining the correct reference pressure is suggested for future project work on this system.

The results obtained while running the engine compare well with those expected from the air-standard cycle. The work output from the real cycle is 23% less than that of the air standard. When the spark advance angle is varied while holding other operating variables constant, the results and indicator diagrams produced are as expected and in line with those presented in the literature.

Further work with the indicator diagram generation system and the Ricardo engine itself could result in a more accurate diagram as well as enabling a more sophisticated analysis of the engine performance. Some recommendations for further work are as follows:

1. Determination of the pressure at the inlet port when the piston is at ODC, at the end of the intake stroke, would enable a correct reference pressure to be assigned. As previously mentioned, at this point the piston is moving slowly and the intake valve is fully open. The pressure in the cylinder can, therefore, be taken as that in the intake manifold. Correct reference pressure assignment allows accurate absolute pressure determination which would be checked by the log-log p-V plot and the pumping loop of motoring data.

2. Determination of the mass flow rate of air into the engine would make the fuel-air ratio known, since the fuel flow rate is presently measurable. This would enable a fuel-air cycle indicator diagram to be generated, which is a much closer theoretical model of the real cycle than is the air standard cycle. The actual indicator diagram could then be further analyzed as explained in the Theory section. Analysis of the fuel-air cycle would also provide a much more sophisticated exercise in thermodynamics than does the air-standard cycle.

3. Adapting the software to allow for the production of an indicator diagram for compression ignition (diesel) running of the engine could be accomplished with a modest effort. Changes would have to be made to

subroutines that deal with cylinder volume assignment, because of the different piston geometries used for the two types of operation.

The suggestions above would increase the accuracy and depth of the analysis possible from a Ricardo engine indicator diagram. The present results, however, are sufficient for many purposes in engine analysis including determination of thermal efficiency, mechanical efficiency, and evaluation of the effects of variation of engine operating conditions. It is hoped that the work represented in this report will serve to increase the value of the Ricardo engine as a research and educational tool.

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APPENDIX A

DERIVATION OF THERMAL EFFICIENCY OF AIR STANDARD OTTO CYCLE IN TERMS OF COMRPESSION RATIO

The compression ratio (r_c) is defined as the ratio of the maximum cylinder volume (volume at ODC) to the minimum volume (volume at IDC), or

$$r_c = \frac{\forall_4}{V_3} = \frac{\forall_1}{\forall_2}$$

The constant entropy, ideal gas processes can be related by

$$S_1 = p_1 \forall_1^{\gamma} = p_2 \forall_2^{\gamma}$$

where γ is the ratio of specific heats of the gas. From the Ideal Gas Law,

$$p\forall = mRT$$

$$p = \frac{mRT}{\forall}$$

$$mRT_1 V_1^{-1} V_1^{\gamma} = mRT_2 V_2^{-1} V_2^{\gamma}$$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \frac{1}{r_c^{\gamma-1}}$$

The result is that, from substituting above into equation [4]

$$\eta_t = 1 - \frac{1}{r_c^{\gamma-1}}$$

APPENDIX B

CALCULATIONS OF ERROR IN CRANK ANGLE DUE TO RISE TIME OF SHAFT ENCODER OUTPUT

The output voltage of the shaft encoder has a rise time of 0.150 msec., during which the voltage increases from 0 to five (5) Volts. The rise time was measured and found to be constant from 250 to 2500 rpm.

In order for the computer software to detect the rise in encoder output, a threshold value is chosen. The software sorts through the digitized encoder ouput downloaded from the oscilloscope and compares it to the threshold value to determine when the encoder output can be called "high". The angle that the crank goes through between the point where the encoder output starts to rise and the point where it reaches the threshold value increases, of course, with rpm.

In the computer software discussed here, the threshold value assigned is 148 vertical increments. The oscilloscope screen contains 256 vertical increments fullscale, so that 148 is 20 increments above 0 Volts. There are 25 increments per vertical division on the scope. The software sets the Volts/division setting of the scope to

2 Volts/division on the channel monitoring the encoder output. The crank angle error due to the risetime of the encoder output will now be calculated at 1200 and 3000 rpm.

$$5 \text{ Volts total rise } \left(\frac{25 \text{ increments/div.}}{2 \text{ Volts/div.}}\right)$$

$$= 62.5 \text{ increments total rise}$$

$$\left(\frac{20 \text{ increments to threshold}}{62.5 \text{ increments total rise}}\right) 0.150 \text{ msec. total risetime}$$

$$= 0.048 \text{ msec. to threshold}$$

Crank angle error at 1200 rpm:

1200 rpm = 20 rev./sec. = 7200 degrees/sec.

7200 degrees/sec.(0.048 msec.) = 0.346 degrees error

Crank angle error at 3000 rpm:

3000 rpm = 50 rev./sec. = 18,000 degrees/sec.

18000 degrees/sec.(0.048 msec.) = 0.864 degrees error

APPENDIX C

COMPUTER SOFTWARE

The software package for the Ricardo engine indicator diagram is original and specifically tailored to the engine geometry. HP Basic, Version 1.0, is the programming language, with Tektronix interfacing commands sent to the oscilloscope in the OUTPUT statements. The software was written to incorporate some desirable features, including flexibility, straight forward directions, optional hardcopies of results, and confirmation of user input. The aim of these features is to make the software as easy, flexible, and efficient to use as possible.

The input demanded from the user by the software includes the engine compression ratio, the range setting of the charge amplifier, and the number of engine cycles to be averaged. The results consist of the following:

Plot of indicator diagram itself

Analysis of data, including

- Gross and net indicated work output of cycle
- Work lost to pumping, or valve, losses
- Indicated mean effective pressure (IMEP)
- Indicated horsepower output
- List of user input (compression ratio, number of cycles averaged)

Listing of modified data: Pressure, Volume, Crank angle

The software consists of the main program and subprograms, both subroutines and functions. The convention of using functions when one value is to be returned and where the subprogram does not interact with the user or the oscilloscope, and subroutines otherwise, was followed. Note that, because of the nature of the HP 9826 computer editor, subprograms cannot be inserted into a file, but must be appended to the end of the file. The subprograms, therefore, do not appear in a logical order in the file listing.

The subprograms, listed under the segments that call them, are as follows:

MAIN program
- Start-up
- Get-offset
- New
  - Get-comp-ratio
  - Get-ca-range
  - Get-num-avg
  - Init-setup
  - Read-avg4-chl
  - Period
  - Scale-hor
  - Turn-on-ch2
  - Scale-ch2-v
    - Max-ch2
  - Acq-ch2
  - Conv-degs
  - Adj-angle
    - Calc-rpm
  - Conv-volume
  - Press
- Graph-ind
- An
  - Calc-rpm
  - Work
    - Trap
  - Horsepower
  - Ind-mep
  - Prnt
- Print-data

A brief explanation of the main program and each subprogram follows, in the order given above.

MAIN Program

```
10    ! Program Name: "IND"
20    !   Ricardo engine indicator diagram
30    !
40    ! By: Peggy A. Faber
50    !
60    ! Written: Summer, 1986
70    !
80    ! Purpose: Generate indicator diagram for
90    !   Ricardo E6 variable compression engine.
100   !   This program is to be used in
110   !   conjunction with the "Ricardo Indicator
120   !   Diagram User's Manual".
130   !
140   ! MAIN PROGRAM:
150   !
160   !Variables and constants:
170   !  Dat: Array holding data
180   !    Column 1: Pressure
190   !    Column 2: Volume
200   !    Column 3: Crank angle
210   !  Idc1, Idc2, Idc3: First, second, and
220   !    third points where shaft encoder output
230   !    goes high, or three IDC's in cycle
240   !  Cr: Compression ratio
250   !  Per: Period of engine cycle
260   !  Ph: Phase of waveform, ie., if IDC1 at
270   !    end of compression stroke or end of
280   !    exhaust stroke
290   !  N: Number of waveforms to be averaged
300   !  Th: Crank angle at which shaft encoder
310   !    output goes high when engine not
320   !    running
330   !
340   !Subprograms used:
350   !  Start_up: Prints brief equipment setup
360   !    instructions on screen
370   !  Get_offset: Inputs crank angle at which
380   !    shaft encoder output goes high
390   !  New: Acquires data for new indicator
400   !    diagram and modifies it
410   !  Graph_ind: Produces plot of indicator
420   !    diagram
430   !  Print_data: Produces hard copy of
440   !    modified data points
```

```
450   !
460   DIM Dat(1024,3)
470   CALL Start_up
480   CALL Get_offset(Th)
490   !Label soft keys
500    ON KEY 0 LABEL "GET DATA" GOTO Dat
510    ON KEY 1 LABEL "PLOT P-V" GOTO Plot_pv
520    ON KEY 2 LABEL " ANALYZE" GOTO A1
530    ON KEY 3 LABEL "HC DATA" GOTO Hc_data
540    ON KEY 4 LABEL "  END" GOTO The_end
550 Spin:    DISP "Press key k0 for a new run"
560          GOTO Spin
570 Dat: CALL New(Dat(*),I1,I2,I3,Cr,Per,Ph,N,Th)
580      GOTO Spin
590 Plot_pv: CALL Graph_ind(Dat(*),I1,I3)
600      GOTO Spin
610 A1:  CALL An(Dat(*),I1,I2,I3,Per,Cr,Ph,N)
620      GOTO Spin
630 Hc_data: CALL Print_data(Dat(*),I1,I3)
640      GOTO Spin
650 The_end: END
```

The main program first calls subroutine Start-up (see section below), which prints a set of brief equipment setup messages on the computer screen. The computer soft keys are then labeled. The soft keys are the set of keys on the computer keyboard which are labeled k0 through k9. When they are pressed, the program executes the GOTO's appearing at the end of the ON KEY statements. The program returns to the line labeled Spin after each subroutine called is completed, and the softkey display is activated so that the user can select the subroutine (New, Graph-ind, An, or Print-data) to be called.

Subroutine Start-up

```
6830   SUB Start_up
6840   !This subroutine prints basic equipment
6850   !set up messages
6860    PRINT "SHAFT ENCODER:"
6870    PRINT " Apply 5 Volts DC excitation"
6880    PRINT "  to shaft encoder."
6890    PRINT " Attach output leads to Ch1 of"
6900    PRINT "  TEK 2530 oscilloscope"
6910    PRINT " "
6920    PRINT "PRESSURE TRANSDUCER:"
6930    PRINT " Attach output from charge"
6940    PRINT "  amplifier to Ch2 of"
6950    PRINT "  TEK 2430 oscilloscope"
6960    PRINT " "
6970    PRINT "MAKE SURE THAT THE OSCILLOSCOPE"
6980    PRINT "OUTPUT SETUP IS AS DESCRIBED"
6990    PRINT "IN USER'S MANUAL:"
7000    PRINT "  ADDRESS: 12"
7010    PRINT "  MODE: T/L"
7020    PRINT "  TERMINATOR: LF/EOI"
7030    PRINT "**Press CONTINUE key to procede"
7040    PAUSE
7050    FOR I=1 TO 18
7060     PRINT " "
7070    NEXT I
7080   SUBEND
```

Subroutine Start-up prints out some basic equipment setup message on the computer screen.

Subroutine Get-offset

```
10900  SUB Get_offset(Theta)
10910  !This subroutine prompts the user to enter
10920  !the crank angle at which the shaft encoder
10930  !output goes high and returns that value.
10940  !
10950  !Variables and constants used:
10960  !   Theta: Angle at which the shaft encoder
10970  !     output goes high (degrees)
10980  !
10990  !Subprograms used: None
11000  !
11010   PRINT "Enter angle (degrees) on flywheel"
11020   PRINT " at which shaft encoder output"
11030   PRINT " goes high then CONTINUE key."
11040   PRINT " "
11050   PRINT "If preferred, input 0 then CONTINUE key "
11060   INPUT Theta
11070   FOR I=1 TO 18
11080    PRINT " "
11090   NEXT I
11100  SUBEND
```

This subroutine acquires the crank angle degree, read from the engine flywheel, at which the shaft encoder output goes high. This value is later used for correction of pressure-volume phasing.

Subroutine New

```
8480   SUB New(Dat(*),I1,I2,I3,Cr,Per,Ph,N,Th)
8490   !This subroutine runs the data gathering
8500   !and calls subroutines that communicate
8510   !with the oscilloscope
8520   !
8530   !Variables and constants used:
8540   !  Dat: Array holding data
8550   !  I1,I2,I3: Data points corresponding to
8560   !    IDC or points where the
8570   !    shaft encoder output goes high
8580   !  Cr: Compression ratio
8590   !  Per: Period of engine cycle
8600   !  Ph: Phase of data
8610   !  N: Number of cycles averaged
8620   !  Th: Crank angle at which shaft encoder
8630   !    output goes high
8640   !
8650   !  Ch1: Array holding waveform from Ch1
8660   !    of scope (shaft encoder)
8670   !  Abort_prog$: String holding boolean
8680   !    value for abortion of data acqui.
8690   !  S_div: Time scale setting on scope
8700   !  V_ch1,V_ch2: Volts/div setting on
8710   !    scope for Ch1 & Ch2, respetively
8720   !  R: Range setting on charge amplifier
8730   !
8740   !Subprograms used:
8750   !  Get_comp_ratio: Inputs compression
8760   !    ratio
8770   !  Get_ca_range: Inputs range setting of
8780   !    charge amplifier
8790   !  Get_num_avg: Inputs number of wave-
8800   !    forms to be averaged
8810   !  Init_setup: Sets initial state of scope
8820   !  Read_avg4_ch1: Acquires waveform from
8830   !    Ch1, averaged over 4
8840   !  Period: Calculates period of engine
8850   !    cycle
8860   !  Scale_hor: Fits one engine cycle to
8870   !    screen horizontally
8880   !  Turn_on_ch2: Displ. Ch2 on scope screen
8890   !  Scale_ch2_v: Scales Ch2 Volts/div to
8900   !    scope screen
8910   !  Acq_ch2: Acquires averaged waveform from
```

```
8920   !    Ch2
8930   !  Conv_degs: Calculates crank angle (degs)
8940   !  Adj_angle: Adjusts crank angle to
8950   !    account for phase error between
8960   !    pressure and crank angle data
8970   !  Conv_volume: Calculates cylinder volume
8980   !    from crank angle
8990   !  Press: Calculates cylinder pressure
9000   !
9010    DIM Ch1(1024),Abort_prog$[5]
9020    OFF KEY 0
9030    OFF KEY 1
9040    OFF KEY 2
9050    OFF KEY 3
9060    OFF KEY 4
9070    Abort_prog$="FALSE"
9080    FOR I=1 TO 18
9090     PRINT " "
9100    NEXT I
9110    !Initialize array
9120     FOR I=1 TO 1024
9130      Dat(I,1)=0
9140      Dat(I,2)=0
9150      Dat(I,3)=0
9160     NEXT I
9170    CALL Get_comp_ratio(Cr)
9180    CALL Get_ca_range(R)
9190    CALL Get_num_avg(N)
9200    FOR I=1 TO 18
9210     PRINT " "
9220    NEXT I
9230    PRINT "GATHERING DATA"
9240    CALL Init_setup(S_div,V_ch1,V_ch2)
9250    CALL Read_avg4_ch1(Ch1(*),S_div)
9260    CALL Period(Ch1(*),S_div,Per,I1,I2,I3)
9270    CALL Scale_hor(Per,S_div)
9280    CALL Turn_on_ch2
9290    CALL Scale_ch2_v(V_ch2,Abort_prog$,S_div)
9300     IF Abort_prog$="TRUE" THEN SUBEXIT
9310    CALL Read_avg4_ch1(Ch1(*),S_div)
9320    CALL Period(Ch1(*),S_div,Per,I1,I2,I3)
9330    CALL Acq_ch2(Dat(*),I1,I2,S_div,Ph,N)
9340    CALL Conv_degs(Dat(*),I1,I2,I3)
9350    CALL Adj_angle(Dat(*),Th,Per,I1,I2,I3)
9360    CALL Conv_volume(Dat(*),Cr,I1,I3)
9370    CALL Press(Dat(*),I1,I2,I3,V_ch2,R,Ph)
9380    FOR I=1 TO 18
9390     PRINT " "
9400    NEXT I
9410    PRINT "DATA GATHERING COMPLETE"
9420   SUBEND
```

Subroutine New performs the entire data acquisition for each run, and converts the raw data to units of pressure, volume and crank angle. It is important to understand the sequence of events in this subroutine to evaluate the significance of the results obtained. New utilizes 13 subprograms to obtain the final data mentioned above. These subprograms will now be explained, except for those that are sufficiently explained by their comments.

Subroutines Get-comp-ratio, Get-ca-range, Get-num-avg

```
4250  SUB Get_comp_ratio(Cr)
4260  !This subroutine acquires the compression
4270  !ratio for this run by prompting the user
4280  !to enter it through the keyboard
4290  !
4300  !Variables and constants used:
4310  !  Cr: Compression ratio
4320  !  Confirm$: Allows user to confirm response
4330  !
4340  !Subprograms used: None
4350  !
4360   DIM Confirm$[1]
4370 Resp:  PRINT "Enter the COMPRESSION RATIO"
4380        PRINT "for this run."
4390        PRINT "Then press CONTINUE key"
4400        INPUT Cr
4410        PRINT " "
4420        PRINT "Are you sure? (Y/N) then CONTINUE"
4430        INPUT Confirm$
4440    IF Confirm$="Y" OR Confirm$="y" THEN
4450     FOR I=1 TO 18
4460      PRINT " "
4470     NEXT I
4480    ELSE
4490     PRINT " "
4500     GOTO Resp
4510    END IF
4520   SUBEND
```

```
5280   SUB Get_ca_range(Range)
5290   !This subroutine prompts the user to enter
5300   !the charge amplifier range
5310   !
5320   !Variables and constants used:
5330   !  Range: Charge ampl. range setting
5340   !    (psi/Volt)
5350   !  Confirm$: Allows user to confirm entry
5360   !
```

```
5370    DIM Confirm$[1]
5380 Resp: PRINT "Enter the charge amplifier RANGE "
5390       PRINT "selected"
5400       PRINT "Then press CONTINUE key"
5410       PRINT " "
5420       INPUT Range
5430       PRINT "are you sure? (Y/N) then CONTINUE"
5440       INPUT Confirm$
5450    IF Confirm$="Y" OR Confirm$="y" THEN
5460     FOR I=1 TO 18
5470      PRINT " "
5480     NEXT I
5490    ELSE
5500     PRINT " "
5510     GOTO Resp
5520    END IF
5530   SUBEND
```

```
10500  SUB Get_num_avg(N)
10510  !This subroutine prompts the user to enter
10520  !the number of engine cycles to be averaged
10530  !over and returns the number.
10540  !
10550  !Variables and constants used:
10560  !  N: Number of waveforms to be averaged
10570  !  Confirm$: String to allow user to
10580  !    confirm input
10590  !
10600  !Subprograms used: None
10610  !
10620   DIM Confirm$[1]
10630 Resp:PRINT "Enter the number of cycles over"
10640     PRINT "which you would like to average"
10650     INPUT N
10660     PRINT " "
10670     PRINT "Are you sure? Y/N then CONTINUE"
10680     INPUT Confirm$
10690   IF Confirm$="Y" OR Confirm$="y" THEN
10700    FOR I=1 TO 18
10710     PRINT " "
10720    NEXT I
10730   ELSE
10740    PRINT " "
10750    GOTO Resp
10760   END IF
10770  SUBEND
```

Get-comp-ratio, Get-ca-range, and Get-num-avg are interactive, prompting the user to enter the compression ratio, charge amplifier range, and the number of cycles to be averaged, respectively, from the computer keyboard. These parameters must be set for each run, and the user is required to confirm the value input.

Subroutine Init-setup

```
680  SUB Init_setup(Sec_div,Volts_ch1,Volts_ch2)
690  ! This subroutine initializes the scope
700  ! settings for each new run
710  !
720  !Variables and constants used:
730  !  Sec_div: Horizontal scope setting
740  !  Volts_ch1,Volts_ch2: Volts/div scope
750  !    setting for Ch1 and Ch2, respectively
760  !
770  !Subprograms used: None
780  !
790   OUTPUT 712;"DEBUG ON"
800   !Set the scope to power-up state
810   OUTPUT 712;"INIT PANEL"
820   WAIT 3
830   !Set up Channels 1&2: Volts/div and sec/div
840   OUTPUT 712;"VMODE CH1:ON,CH2:OFF"
850   OUTPUT 712;"CH1 VOLTS:2"
860   Volts_ch1=2
870   OUTPUT 712;"CH2 VOLTS:2"
880   Volts_ch2=2
890   OUTPUT 712;"HOR ASEC:.1"
900   Sec_div=.1
910   !Trigger from Channel 1 on positive
920   !slope of square wave
930   OUTPUT 712;"ATRIG MOD:NOR,SOU:CH1"
940   OUTPUT 712;"ATRIG COU:DC,LEV:2"
950   OUTPUT 712;"ATRIG SLO:PLU,POS:1"
960   OUTPUT 712;"RUN ACQUIRE"
970  SUBEND
```

Init-setup initializes the scope settings so that they are the same at the start of each run. The "INIT PANEL" OUTPUT statement sets all scope settings to the powerup state (see 2430 Instrument Interfacing Guide, pgs. 24-

25). The "VMODE" statement turns Channel 1 on and Channel 2 off on the scope display. The scope scale settings are then set at 2 Volts/div. (CH1 VOLTS and CH2 VOLTS), and the horizontal scale is set to 100 msec./div. (HOR ASEC). This horizontal setting allows 2 secs. of Channel 1 data to be displayed on the screen, which means that the engine can be running at as few as 60 rpm for an entire engine cycle (2 encoder cycles) to be captured.

The "ATRIG" commands control the trigger settings of the scope. The trigger mode (MOD) is set to NORMAL, which means that the trigger source (Ch1) must be specified as well as the coupling (COU:DC), the level (2 Volts, from the LEV:2 command), and the slope (positive, from the SLO:PLU command). This means that the scope triggers when the shaft encoder goes high. The trigger position, "POS", setting of "1" places the trigger point at the leftmost position possible on the waveform captured, so that a maximum number of data points occurs after the trigger. The trigger point is, therefore, off the screen, since at powerup, the scope displays the central 10 horizontal divisions out of the 20 divisions of data captured. To observe the trigger point, use the HORIZONTAL POSITION knob on the front panel of the scope.

The last output statement in Init-setup is "RUN ACQUIRE", which causes the scope to begin waveform acquisition from Channel 1 under the conditions set. This subroutine prepares the scope for the actual initial waveform downloading to the computer.

Subroutine Read-avg4-ch1

```
1000 SUB Read_avg4_ch1(A(*),S_div)
1010 !Acquire binary data from Channel 1
1020 !averaging over 4 waves
1030 !
1040 !Variables and constants used:
1050 !  A: 1-D array to hold waveform
1060 !  S_div: Scope time scale setting
1070 !
1080  OUTPUT 712;"DATA ENC:RPB,SOU:CH1"
1090  OUTPUT 712;"ACQUIRE MODE:AVG,NUMAV:4"
1100  WAIT 40*S_div*4
1110  !Get waveform
1120  OUTPUT 712;"CURVE?"
1130  ENTER 712 USING "#,B";A(*)
1140  OUTPUT 712;"ACQ MODE:NORMAL"
1150 SUBEND
```

The Read-avg4-ch1 subroutine acquires the waveform from Channel 1, averaged over 4 acquisitions, and downloads it to the computer. It was found that averaging over 4 waveforms produces a sufficiently smooth result that it can be analyzed by the Period subroutine (below). If less than 4 waveforms were averaged, the rising edge of the resultant curve is sometimes too rough for use in Period.

The DATA specified in the first OUTPUT statement specifies the data source for the acquisition to be Channel 1, the shaft encoder. The data encoding (ENC:RPR) is set to Right Justified Positive Binary, which means that the data is encoded in 256 vertical increments, from 0 to 255, with 0 volts

corresponding to the integer 127. "ACQUIRE MODE:AVG, NUMAVG:4" sets the scope to acquire in the AVERAGE mode over 4 waveforms.

The WAIT statement allows time for the waveforms to be acquired and averaged. The resultant waveform is then requested using the "CURVE?" command and is entered into the computer with the ENTER statement, specifying binary encoding (B), into array A. Array A is a column array for maximum speed of data downloading. The last OUTPUT statement then returns the acquisition mode to NORMAL, the mode assumed initially by the subprograms which follow.

Subroutine Period

```
1250 SUB Period(A(*),Sec_div,Per,Idc1,Idc2,Idc3)
1260 !This subroutine finds the period of two
1270 !cycles of the square wave (one engine cycle)
1280 !
1290 !Variables and constants used:
1300 !  A: Array containing waveform
1310 !  Sec_div: Horizontal scope setting
1320 !  Per: Period of engine cycle (secs.)
1330 !  Idc1,Idc2,Idc3: Points in cycle where
1340 !    shaft encoder signal goes high
1350 !  Level: Vertical value that waveform
1360 !    must cross to be considered "high"
1370 !
1380 !Subprograms used: None
1390 !
1400  Level=148
1410 Find_idc1: FOR I=1 TO 1024
1420   IF (A(I)>=Level AND A(I-1)<Level) THEN
1430    Idc1=I
1440    GOTO Find_idc2
1450   END IF
1460   NEXT I
1470 Find_idc2: FOR I=Idc1+1 TO 1024
1480   IF (A(I)>Level AND A(I-1)<Level) THEN
1490    Idc2=I
1500    GOTO Find_idc3
1510   END IF
1520   NEXT I
1530 Find_idc3:  FOR I=Idc2+1 TO 1024
1540   IF (A(I)>Level AND A(I-1)<Level) THEN
1550    Idc3=I
1560    GOTO Perio
1570   END IF
1580   NEXT I
1590 Perio:  Per=(Idc3-Idc1)*Sec_div/50
1600   Idc2=INT((Idc1+Idc3)/2)
1610   SUBEND
```

Period determines the period of one engine cycle (two shaft rotations) and records the data points at which the shaft encoder output goes high. It does this by looking at the binary values of the waveforms and finding the first and third points where the curve crosses the threshold value of 148 vertically. These points correspond approximately to the first and third times the piston reaches inner dead center, or the first and last points of the engine cycle. The period is then calculated using the sec./div. value, and the second IDC point is assigned to a data point midway between the first and third IDC's, since constant angular velocity is assumed. The period and the three IDC's are returned to the calling program. Subroutine Period is called twice by New, the first time to get an initial value of the cycle period and again after the horizontal setting of the scope has been scaled for maximum resolution (see Scale-hor). This is done so that slight variations of rpm with time have a minimal effect in the diagram.

Subroutine Scale-hor

```
1640   SUB Scale_hor(Per,Time_div)
1650   !Adjusts the horizontal (time) scale so
1660   !that two periods of the square wave are
1670   !in as much of the 20 time scale divisions
1680   !as possible
1690   !
1700   !Variables and constants used:
1710   !  Per: Period of engine cycle (secs.)
1720   !  Time_div: Horizontal scale scope setting
1730   !    (sec./div.)
1740   !
1750   !Subprograms used: None
1760   !
1770    IF Per<=19 AND Per>9.5 THEN
1780     OUTPUT 712;"HOR ASEC:1.0"
1790     Time_div=1.0
1800     SUBEXIT
1810    END IF
1820    IF Per<=9.5 AND Per>3.8 THEN
1830     OUTPUT 712;"HOR ASEC:.5"
1840     Time_div=.5
1850     SUBEXIT
1860    END IF
1870    IF Per<=3.8 AND Per>1.9 THEN
1880     OUTPUT 712;"HOR ASEC:.2"
1890     Time_div=.2
1900     SUBEXIT
1910    END IF
1920    IF Per<=1.9 AND Per>.95 THEN
1930     OUTPUT 712;"HOR ASEC:.1"
1940     Time_div=.1
1950     SUBEXIT
1960    END IF
1970    IF Per<=.95 AND Per>.38 THEN
1980     OUTPUT 712;"HOR ASEC:.05"
1990     Time_div=.05
2000     SUBEXIT
2010    END IF
2020    IF Per<=.38 AND Per>.19 THEN
2030     OUTPUT 712;"HOR ASEC:.02"
2040     Time_div=.02
2050     SUBEXIT
```

```
2060     END IF
2070     IF Per<=.19 AND Per>.095 THEN
2080      OUTPUT 712;"HOR ASEC:.01"
2090      Time_div=.01
2100      SUBEXIT
2110     END IF
2120     IF Per<=.095 AND Per>.038 THEN
2130      OUTPUT 712;"HOR ASEC:.005"
2140      Time_div=.005
2150      SUBEXIT
2160     END IF
2170     IF Per<=.038 THEN
2180      OUTPUT 712;"HOR ASEC:.002"
2190      Time_div=.002
2200     END IF
2210    SUBEND
```

Scale-hor sets the horizontal, seconds/division, scale so that two cycles of the waveform takes up as much of the scope screen as possible to provide maximum horizontal resolution of the waveform. It does this by a series of IF statements which set the horizontal scale according to the period of two encoder output periods, or one engine cycle. The HOR ASEC: output statements sends the sec./div. value to the oscilloscope, and the "Time-div" variable is returned to the rest of the subprograms through the parameter list. The subroutine is then exited by the SUBEXIT statement.

Subroutine Turn-on-ch2

```
1180 SUB Turn_on_ch2
1190 !This subroutine turns on Ch2
1200 OUTPUT 712;"VMODE CH2:ON"
1210 WAIT 1
1220 SUBEND
```

This subroutine simply causes Channel 2 to be displayed on the oscilloscope screen by outputting the "VMODE CH2:ON" statement. The program then waits for 1 second to allow the Channel 2 trace to appear on the screen, since it will not be displayed unless the scope is triggered form Channel 1.

Subroutine Scale-ch2-v

```
2240   SUB Scale_ch2_v(Volts_ch2,Fatal_error$,S)
2250   !This subroutine scales the Volts/div on
2260   !Ch2 so thew waveform fits the screen
2270   !vertically as closely as possible
2280   !
2290   !Variables and constants used:
2300   !  Volts_ch2: Volts/div setting of Ch2 on
2310   !    the scope
2320   !  Fatal_error: String to hold boolean
2330   !    value for abortion of data acqui.
2340   !  S: Horizontal scale setting of scope
2350   !  Max: Maximum value of waveform
2360   !  Interval: Time (in sec.) to wait for
2370   !    scope to digitize input
2380   !
2390   !Subprograms used:
2400   !  FNMax_ch2: Returns maximum vertical
2410   !    value of 20 waveforms
2420   !
2430    Interval=20*S+1
2440 Reduce:  !Reduce height of waveform if it
2450          !runs off the screen
2460   Max=FNMax_ch2(S)
2470   IF Max>=125 THEN
2480    OUTPUT 712;"CH2 VOLTS:5"
2490    WAIT Interval
2500    Volts_ch2=5
2510   ELSE
2520    GOTO Enlarge
2530   END IF
2540   IF FNMax_ch2(S)>=125 THEN
2550    OUTPUT 712;"CH2 VOLTS:10"
2560    WAIT Interval
2570    Volts_ch2=10
2580   ELSE
2590    SUBEXIT
2600   END IF
2610   IF FNMax_ch2(S)>=125 THEN
2620    OUTPUT 712;"CH2 VOLTS:20"
2630    WAIT Interval
2640    Volts_ch2=20
2650   ELSE
```

```
2660     SUBEXIT
2670    END IF
2680    IF FNMax_ch2(S)>=125 THEN
2690     OUTPUT 712;"CH2 VOLTS:50"
2700     WAIT Interval
2710     Volts_ch2=50
2720    ELSE
2730     SUBEXIT
2740    END IF
2750    IF FNMax_ch2(S)>=125 THEN
2760     !The input to Ch2 is too great in
2770     !amplitude to handle
2780     PRINT "FATAL PROBLEM"
2790     PRINT " The amplitude of the input from"
2800     PRINT " Ch2 is too great for the program"
2810     PRINT " to handle."
2820     PRINT " Adjust and begin again"
2830     Fatal_error$="TRUE"
2840     SUBEXIT
2850    END IF
2860 Enlarge:  !Enlarge the vertical scale so that
2870           !the waveform covers as much of the
2880           !scale as possible
2890    IF Max<63 THEN
2900     OUTPUT 712;"CH2 VOLTS:1"
2910     WAIT Interval
2920     Volts_ch2=1
2930    ELSE
2940     SUBEXIT
2950    END IF
2960    IF FNMax_ch2(S)<63 THEN
2970     OUTPUT 712;"CH2 VOLTS:.5"
2980     WAIT Interval
2990     Volts_ch2=.5
3000    ELSE
3010     SUBEXIT
3020    END IF
3030    IF FNMax_ch2(S)<50 THEN
3040     OUTPUT 712;"CH2 VOLTS:.2"
3050     WAIT Interval
3060     Volts_ch2=.2
3070    ELSE
3080     SUBEXIT
3090    END IF
3100    IF FNMax_ch2(S)<63 THEN
3110     OUTPUT 712;"CH2 VOLTS:.1"
3120     WAIT Interval
3130     Volts_ch2=.1
3140    ELSE
3150     SUBEXIT
```

```
3160    END IF
3170    IF FNMax_ch2(5)<63 THEN
3180     OUTPUT 712;"CH2 VOLTS:.05"
3190     WAIT Interval
3200     Volts_ch2=.05
3210    ELSE
3220     SUBEXIT
3230    END IF
3240    IF FNMax_ch2(5)<50 THEN
3250     OUTPUT 712;"CH2 VOLTS:.02"
3260     WAIT Interval
3270     Volts_ch2=.02
3280    END IF
3290   SUBEND
```

Like Scale-hor, Scale-ch2-v maximizes the resolution of the data. Scale-ch2-v sets the vertical, volts/div., scale of channel 2 so that the pressure data occupies as much of the scope screen vertically as possible. This subroutine performs the scale adjustment differently than the horizontal scale was adjusted, however. Here, the vertical scale is changed if the conditions of the IF statement are met (if the waveform runs off the screen or if the waveform could be expanded further), and then the maximum value is checked again to see if further adjustment is needed. It is done this way for the vertical scale because, if the waveform runs off the screen, it must obviously be scaled and then checked that it is all on the screen. If the waveform must be expanded, it may have a maximum value so small that the resolution of 1/126 returned by Max-ch2 would not be sufficient to select the correct vertical scale directly as was done in Scale-hor. Now this subprogram will be explained step-by-step.

First, the time (Interval) is calculated that the program must pause for the scope to adjust the volts/div. of Channel 2 and acquire a new waveform before the maximum value of the waveform is looked at by function Max-ch2 (see section below). In the lines after the Reduce line label, the program increases the Volts/div. value if needed, based on the value returned by Max-ch2. Function Max-ch2 returns the maximum value of twenty waveforms on Channel 2 (read the section on FNMax-ch2 now), which is between -127 and 126. If the waveform does not need to be reduced, the program goes to the line labeled "Enlarge" to check the fit of the waveform to the screen. Fatal-error is set to "TRUE" if, after the vertical scale has been set to its maximum value of 50 Volts/div, the waveform still goes off the screen. The segment after the line labeled "Enlarge" decrease the Volts/div. value in a minimum of 20 mV/div. The new Volts/div setting for Channel 2 it sent back through the parameter list in the Volts-ch2 variable.

The time taken to execute this subprogram is worthwhile, since there is a maximum vertical resolution of the waveform of only 1/256, which must be exploited as fully as possible.

Function FNMax-ch2

```
3320  DEF FNMax_ch2(S)
3330  !This function finds the maximum value of
3340  !waveform on Ch2 on a scale of -127 to 126.
3350  !Twenty waveforms are sampled.
3360  !
3370  !Variables and constants used:
3380  !  S: Horizontal scale setting of scope
3390  !  Max: Maximum vertical value of
3400  !    waveforms so far
3410  !  Greatest: Max vertical value for
3420  !    individual waveform
3430  !  Interval: Time to wait for scope to
3440  !    acquire curve
3450  !
3460   OUTPUT 712;"START 1;STOP 1024"
3470   OUTPUT 712;"VMODE CH2:ON"
3480   OUTPUT 712;"DATA SOU:CH2"
3490   Interval=20*S+1
3500   Max=-500
3510   FOR I=1 TO 20
3520    OUTPUT 712;"ACQ MOD:NOR"
3530    WAIT Interval
3540    OUTPUT 712;"MAXIMUM?"
3550    ENTER 712;Greatest
3560    IF Greatest>Max THEN
3570     Max=Greatest
3580    END IF
3590   NEXT I
3600   RETURN Max
3610  FNEND
```

Max-ch2 returns the maximum vertical value of twenty waveforms sampled on Channel 2. This maximum value lies between -127 and 126, the full-scale range of the scope screen. The datapoints of the waveform from the

START (1) to STOP (1024), the entire curve, are considered. Channel 2 is turned on (VMODE statement), and the data source is specified as Channel 2 (DATA SOU statement). In the FOR/NEXT loop, the waveform is acquired while the program is pausing due to the WAIT statement. The scope sends the maximum vertical value of the curve in response to the MAXIMUM? request, which is entered into the variable "Greatest". The IF statement assigns the value in "Greatest" to "Max" if it is the highest so far. This is repeated for twenty waveform acquisitions, and the value of "Max" is returned by the function.

Twenty waveforms are checked by this function because, if the engine is running roughly, there is a large fluctuation in peak pressure between cycles. If part of the curve acquired does not fit on the scope screen vertically, the data points are digitized to a value of 0 Volts, instead of their true values. This, of course, plays havoc with the results, and the program attempts to avoid this situation by scaling vertically based on the maximum pressure of twenty cycles.

Now that the horizontal time scale and the vertical scale of Channel 2 have been adjusted, the waveforms that will be used for the indicator diagram can be acquired.

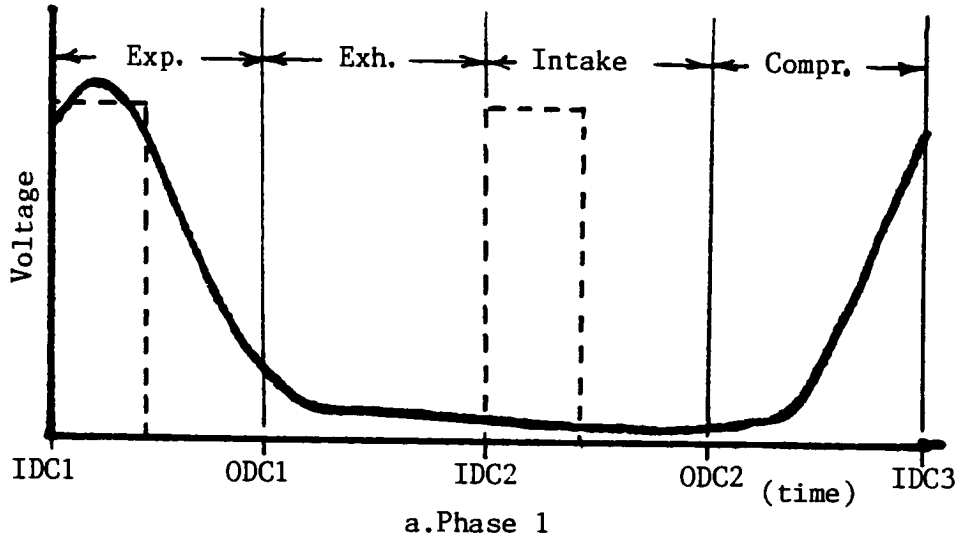
Subroutine Acq-ch2

```
3640  SUB Acq_ch2(8(*),I1,I2,S_div,Phase,N)
3650  !This subroutine acquires the output curve
3660  !based on the average of N cycles
3670  !
3680  !Variables and constants used:
3690  !  8: 2-D array to store data
3700  !  I1,I2: Points where shaft encoder
3710  !    output goes high
3720  !  S_div: Horizontal scale scope setting
3730  !  Phase: Indicates if I1 occurs at end of
3740  !    compression stroke (Phase=1) or at
3750  !    end of exhaust stroke (Phase=2)
3760  !  N: Number of waveforms to be averaged
3770  !  A: Temporary array to receive down-
3780  !    loaded waveform
3790  !  Id1,Id2: Arrays to collect waveform data
3800  !    for each phase
3810  !  Count1,Count2: Counters for number of
3820  !    waveforms kept in Id1 and Id2,
3830  !    respectively
3840  !  Interval: Time to wait for scope to
3850  !    acquire waveform
3860  !
3870  !Subprograms used: None
3880  !
3890   DIM A(1024),Id1(1024),Id2(1024)
3900   Interval=20*S_div+1
3910   OUTPUT 712;"VMODE CH2:ON"
3920   OUTPUT 712;"DATA ENC:RPB,SOU:CH2"
3930 R_ch2:  OUTPUT 712;"ACQUIRE MOD:NORMAL"
3940   WAIT Interval
3950   OUTPUT 712;"CURVE?"
3960   ENTER 712 USING "#,B";A(*)
3970   IF A(I1)>A(I2) THEN
3980    FOR I=1 TO 1024
3990     Id1(I)=Id1(I)+A(I)
4000    NEXT I
4010    Count1=Count1+1
4020   ELSE
4030    FOR I=1 TO 1024
4040     Id2(I)=Id2(I)+A(I)
4050    NEXT I
```

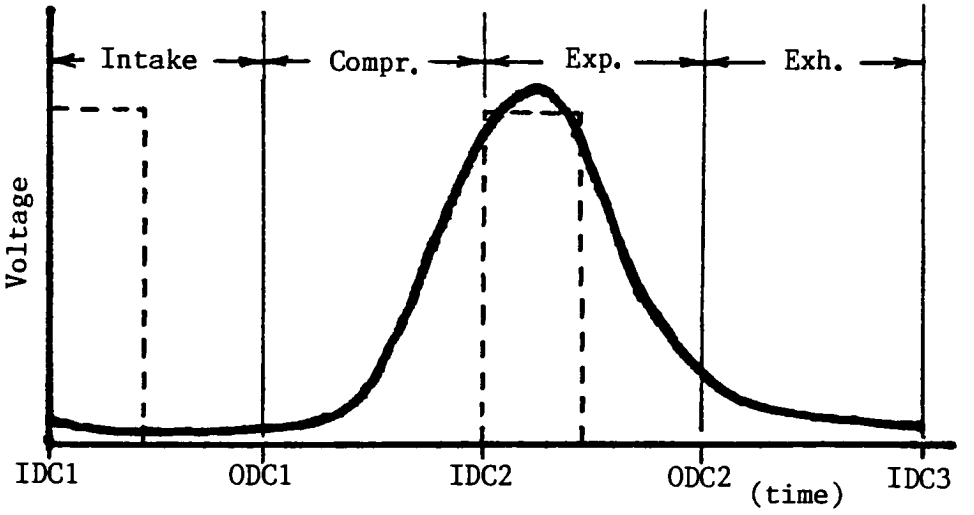
```
4060     Count2=Count2+1
4070    END IF
4080    IF Count1<N AND Count2<N THEN
4090     GOTO R_ch2
4100    END IF
4110    IF Count1=N THEN
4120     FOR I=1 TO 1024
4130      B(I,1)=Id1(I)/N
4140     NEXT I
4150     Phase=1
4160    ELSE
4170     FOR I=1 TO 1024
4180      B(I,1)=Id2(I)/N
4190     NEXT I
4200     Phase=2
4210    END IF
4220   SUBEND
```

The purpose of subroutine Acq-ch2 is to acquire the curve from Channel 2, and average over N waveforms. The phase of the resultant curve must also be returned through the parameter statement. Since the engine cycle occurs over two rotations of the drive shaft, the signal from the shaft encoder goes high twice per engine cycle. Thus, the scope can be triggered at two points in the engine cycle, so that it captures two types of curves (see Fig A1 below). These curve types must be kept sorted, with the result based on only one type (or one phase). With this understood, this subroutine will now be explained.

Three internal arrays are used in this subroutine. Array A allows the fast downloading of the waveform from the oscilloscope. Arrays Id1 and Id2 store the cumulative data for phase 1 and phase 2 type waveforms, respectively, after sorting. The first two OUTPUT statements turn on the



a.Phase 1



b.Phase 2

-- Encoder Output
— Pressure Output

Fig.A1
Locations of Piston Strokes in Phases 1 & 2

Channel 2 display, set the data encoding, and specify the data source of the acquisition. The interval ("Interval") to be waited for acquisition and downloading of data is then calculated, and the phase counters are set to zero.

The line label Rch2 (for "read channel 2") marks the beginning of the program segment to be repeated until N waveforms of either phase type have been acquired. The acquire mode is set to Normal, the curve requested, and the waveform downloaded into array A. The first IF/THEN/ELSE sorts the waveforms by phase, loads the arrays, and increments the counters. The IF checks the counters to determine if N waveforms of either phase have been acquired, and returns control to line Rch2 if both counters are less than N. The second IF/THEN/ELSE loads the averaged waveform into the data array B to be passed through the parameter list and assigns a value to Phase for use later in the program.

Subroutine Conv-degs

```
4550   SUB Conv_degs(B(*),Idc1,Idc2,Idc3)
4560   !This subroutine converts from horizontal
4570   !index points to degrees and stores these
4580   !in column 3 of array B(*).
4590   !Constant angular velocity is assumed.
4600   !
4610   !Variables and constants used:
4620   !  B: Array holding data
4630   !  Idc1,Idc2,Idc3: Points where shaft
4640   !    encoder output goes high
4650   !  Increment: Increment in degrees between
4660   !    data points
4670   !
4680   !Subprograms used: None
4690   !
4700    Increment=720/(Idc3-Idc1)
4710    B(Idc1,3)=0
4720    B(Idc2,3)=0
4730    B(Idc3,3)=0
4740    J=1
4750    FOR I=Idc1-1 TO 1 STEP -1
4760     B(I,3)=360-Increment*J
4770     J=J+1
4780    NEXT I
4790    FOR I=Idc1+1 TO Idc2-1
4800     B(I,3)=B(I-1,3)+Increment
4810    NEXT I
4820    FOR I=Idc2+1 TO 1024
4830     B(I,3)=B(I-1,3)+Increment
4840    NEXT I
4850   SUBEND
```

Conv-degs fills the second column of the data array, here called array R, with the crank angle in degrees. The critical assumption used is that the angular velocity of the drive shaft is constant. The formula for calculating the

increment is, therefore, simply 2x360 (two shaft rotations, in degrees) divided by the number of data points in one engine cycle.

Subroutine Adj-angle

```
11130  SUB Adj_angle(Dat(*),Th,Per,Idc1,Idc2,Idc3)
11140  !This subroutine adjusts the crank angle
11150  !data to account for the phase error in
11160  !pressure and encoder input due to the
11170  !flexible coupling and misalignment
11180  !of crankshaft and encoder shaft. The
11190  !calibration equation is based on
11200  !motoring data.
11210  !
11220  !Variables and constants used:
11230  !  Dat: Array holding data
11240  !  Th: Crank angle at which the shaft
11250  !    encoder output goes high when
11260  !    engine not running (in degrees)
11270  !  Per: Period of engine cycle
11280  !  Idc1,Idc2,Idc3: Points where piston at
11290  !    inner dead center
11300  !  Rpm: Rev/min of engine
11310  !  Offset: Angular offset (phase error)
11320  !    of pressure and crank angle data
11330  !    (in degrees)
11340  !  Frac_angle: proportion of crank shaft
11350  !    revolution in error
11360  !  Adj_idc: Number of data points by
11370  !    which the IDC data points must be
11380  !    shifted due to phase error
11390  !  Angle: Adjusted crank angle (degrees)
11400  !
11410  !Subprograms used:
11420  !  Calc_rpm: Calculates rev/min of engine
11430  !
11440   Rpm=FNCalc_rpm(Per)
11450   IF Th>180 THEN
11460    Th=Th-360
11470   END IF
11480   Offset=.0095680*Rpm-1.23877-Th
11490   Frac_angle=Offset/360
11500   Adj_idc=INT(Frac_angle*(Idc2-Idc1))
11510   IF Frac_angle<0. THEN
11520    Adj_idc=-Adj_idc
11530   END IF
```

```
11540    Idc1=Idc1+Adj_idc
11550    Idc2=Idc2+Adj_idc
11560    Idc3=Idc3+Adj_idc
11570   FOR I=Idc1 TO Idc3
11580    Angle=Dat(I,3)-Offset
11590    IF Angle<0. THEN
11600     Angle=360+Angle
11610    END IF
11620    IF Angle>360 THEN
11630     Angle=Angle-360
11640    END IF
11650    Dat(I,3)=Angle
11660   NEXT I
11670  SUBEND
```

The Adj-angle subroutine makes use of motoring data analysis to correct the phasing between pressure and crank angle data. The correction is based on the engine rpm and the alignment between the shaft of the shaft encoder and the drive shaft, as expressed in equation [10].

The subroutine performs two tasks, adjusting the angle value and adjusting the data points assigned to be IDC's. The value of the phase error ("Offset") is calculated from the relation obtained between rpm and phase error from motoring data. The IDC's are then adjusted accordingly. Then the angle values are adjusted in the FOR-NEXT loop.

Subroutine Conv-volume

```
4860   !
4870   !
4880   SUB Conv_volume(8(*),R,Idc1,Idc3)
4890   !This subroutine converts the crankangle
4900   !values from radians to cylinder volume
4910   !in in.**3.
4920   !
4930   !Variables and constants used:
4940   !  B: Array holding data
4950   !  R: Compression ratio
4960   !  Idc1,Idc3: Beginning and end pooints
4970   !    of cycle waveform
4980   !  S,D,L: Defined below
4990   !  Vo: Clearance volume
5000   !  Epsi,Epsi_sq,A,C,Const: Used to save
5010   !    computation time
5020   !  X: Crank angle for data point
5030   !
5040   !Subprograms used: None
5050   !
5060    DEG
5070    !The following are parameters set by the
5080    !geometry of the Ricardo engine (inches)
5090     S=4.375     !Piston stroke
5100     D=3.000     !Cylinder bore
5110     L=9.500     !Rod length
5120    !
5130    Vo=.25*PI*D*D*S/(R-1)
5140    !Further values to save computation time
5150     Epsi=S/(2*L)
5160     Epsi=Epsi*Epsi
5170     A=Vo*(R-1)/2
5180     C=A/Epsi
5190     Const=Vo+A+C
5200    !Compute volumes
5210     FOR I=Idc1 TO Idc3
5220      X=B(I,3)
5230      B(I,2)=Const-A*COS(X)-C*SQR(1-Epsi_sq*(SIN(X))^2)
5240     NEXT I
5250   SUBEND
```

Conv-volume converts the values in column 2 of the data array (array B) from degrees of crank angle to cylinder volume. The subroutine implements the following formula (ref. 8, pg 172) for cylinder volume:

$$V = V_0\left[1 + \frac{r-1}{2}\{1 - \cos\Theta + \frac{1}{\varepsilon}[1 - (1 - \varepsilon^2 \sin^2\Theta)^{\frac{1}{2}}]\}\right] \qquad [11]$$

where: V = cylinder volume

V_0 = clearance volume

r = compression ratio

Θ = crank angle

and

$$\varepsilon = \frac{S}{2L}$$

where: S = stroke length

L = connecting rod length

Subroutine Press

```
5560   SUB Press(C(*),I1,I2,I3,V_div,R,Ph)
5570   !This subroutine converts the input from
5580   !the pressure transducer to pressure units
5590   !(psia). It takes the pressure when the
5600   !piston is at ODC at the end of the
5610   !suction stroke as equaling the pressure
5620   !in the intake manifold, approximating
5630   !that to be 14.7 psia.
5640   !
5650   !Variables and constants used:
5660   !  C: Array holding data
5670   !  I1,I2,I3: Points at inner dead center
5680   !  V_div: Volts/div setting of Ch2
5690   !  R: Range setting of charge amplifier
5700   !    in psi/Volt
5710   !  Ph: Phase of pressure waveform
5720   !    Ph=1 if I1 at end of compression
5730   !    Ph=2 if I1 at end of exhaust
5740   !  Odc1,Odc2: Point at ODC after suction
5750   !    stroke
5760   !  Ref: Reference point in cycle, end of
5770   !    suction stroke
5780   !  Conv_factor: Conversion factor from
5790   !    vertical value to psi
5800   !
5810   !Subprograms used: None
5820   !
5830    !Determine ODC after suction stroke
5840    IF Ph=1 THEN
5850     Odc2=INT((I3+I2)/2)
5860     Ref=C(Odc2,1)
5870    END IF
5880    IF Ph=2 THEN
5890     Odc1=INT((I1+I2)/2)
5900     Ref=C(Odc1,1)
5910    END IF
5920    Conv_factor=R*V_div/25
5930    FOR I=I1 TO I3
5940     C(I,1)=14.7+Conv_factor*(C(I,1)-Ref)
5950    NEXT I
5960   SUBEND
```

Subroutine Press calculates the pressure of each data point in the cycle, and substitutes the pressure value (in psia) for the previous value (in vertical increments) in column 1 of the data array. The assumption that this subroutine is based on, as is mentioned in the comment, is that the pressure in the cylinder at the end of the suction stroke is approximately atmospheric pressure (about 14.7 psia). Taylor (ref. 1) states that this approximation can be made for many engines because, at this point in the cycle, the piston has been moving very slowly and the intake valve is fully open.

Because of the encoding of the data (RPB) from the pressure transducer, the vertical values lie between 0 and 256. These units must be converted to pressure. The IF/THEN/ELSE section of the subroutine determines which data point corresponds approximately with the end of the suction stroke, based on the phase of the averaged waveform. The value of this data point ("Ref"), is assigned the known reference pressure as explained above.

The conversion factor (Conv-factor) converts from vertical increment value to psi as follows:

$$\text{Con-factor} = R \star V - \text{div}/25 \qquad [12]$$

where: R = the charge amplifier range setting in psi/Volt

V - div = the Ch 2 vertical setting of the scope in Volts/div

25 = the number of vertical increments per scope division

The resulting units of Conv-factor are psi/vertical increment. The FOR/NEXT loop does the actual conversion for each data point using the conversion factor and the reference point value.

Subroutine Graph-ind

```
5990   SUB Graph_ind(C(*),Idc1,Idc3)
6000   !This subprogram plots the indicator
6010   !diagram and produces a hard copy if
6020   !desired.
6030   !
6040   !Variables and constants used:
6050   !  C: Array holding data
6060   !  Idc1,Idc3: Beginning and end points of
6070   !    data
6080   !  Resp$: String holding user's response to
6090   !    whether hard copy of plot desired
6100   !  Maxp: Maximum pressure value
6110   !  Maxv,Minv: Max and min volume values
6120   !  Top_axis: Max value of vertical axis
6130   !  Right_axis: Max value of horizontal
6140   !    axis
6150   !  Left_axis: Min value of horizontal axis
6160   !
6170   !Subprograms used:
6180   !
6190    DIM Resp$[1]
6200    OFF KEY 0
6210    OFF KEY 1
6220    OFF KEY 2
6230    OFF KEY 3
6240    OFF KEY 4
6250    GINIT
6260    GRAPHICS ON
6270    FOR I=1 TO 18
6280     PRINT " "
6290    NEXT I
6300    !Find extrema of data for scaling
6310    LET Maxp=-500
6320    LET Maxv=-500
6330    LET Minv=500
6340    FOR I=Idc1 TO Idc3
6350     IF C(I,1)>Maxp THEN Maxp=C(I,1)
6360     IF C(I,2)>Maxv THEN Maxv=C(I,2)
6370     IF C(I,2)<Minv THEN Minv=C(I,2)
6380    NEXT I
6390    !Scale axes
6400    Top_axis=INT(Maxp+.5)+10
6410    Right_axis=INT(Maxv+.5)+1
```

```
6420     Left_axis=-5
6430     WINDOW Left_axis,Right_axis,-20,Top_axis
6440     AXES 5,10,0,0,2,5
6450     !Label axes
6460     LORG 9
6470     MOVE Right_axis-2,Top_axis-10
6480     LABEL "P (psia) vs V (in**3)"
6490     LORG 6
6500     FOR I=Left_axis TO Right_axis STEP 5
6510      MOVE I,0
6520      LABEL I
6530     NEXT I
6540     LORG 8
6550     FOR I=50 TO Top_axis STEP 50
6560      MOVE 0,I
6570      LABEL I
6580     NEXT I
6590     !Plot curve
6600     MOVE C(Idc1,2),C(Idc1,1)
6610     FOR I=Idc1+1 TO Idc3
6620      DRAW C(I,2),C(I,1)
6630     NEXT I
6640     !Prompt for hardcopy
6650     PRINT "Press 'P' for a hard copy"
6660     PRINT "or 'Q' to proceed then CONTINUE"
6670     PRINT " "
6680 Choice:   INPUT Resp$
6690     IF Resp$="Q" OR Resp$="q" THEN
6700      GRAPHICS OFF
6710      GCLEAR
6720      FOR I=1 TO 18
6730       PRINT " "
6740      NEXT I
6750     END IF
6760     IF Resp$="P" OR Resp$="p" THEN
6770      DUMP GRAPHICS #701
6780      GOTO Choice !Can make multiple copies
6790     END IF
6800    SUBEND
```

Subroutine Graph-ind plots the indicator diagram itself on the computer screen and produces a hard copy if desired by the user. The axes are scaled to

the data for maximum resolution of the plot. The more important commands and logic of this subroutine will now be explained.

GINIT establishes a set of default values for the graphics operations, and GRAPHICS ON turns the computer graphics display on. The screen is then cleared of all printed messages by the first FOR/NEXT loop. The next section finds the maximum and minimum volume values and the maximum pressure value in the data, and the extrema of the axes are set in the WINDOW statement. The AXES statement sets the axis locations and the tic spacing. LORG and LABEL are used to label the axis increments and the diagram itself (see BASIC Language Reference for HP Series 200 Computers for details on these and other commands). The MOVE statement moves the pen without drawing a line on the path moved, while DRAW causes a line to be left in the pen path. The last 12 lines of the subroutine prompt the user as to whether a hard copy of the plot is desired, and produces the printout. Multiple copies can be made by responding with "P" more than once at the prompt.

The smoothness of this plot is limited by the resolution of the data and the resolution of the computer screen and printer. However, increasing the number of waveforms averaged produces a smoother plot.

Subroutine An

```
9450   SUB An(A(*),I1,I2,I3,Per,Cr,Ph,N)
9460   !This subroutine calls subroutines that
9470   !analyze the results, determining work,
9480   !horsepower, and IMEP.
9490   !The results are then printed on the screen
9500   !with the option of a hardcopy.
9510   !
9520   !Variables and constants used:
9530   !  A: Array holding data
9540   !  I1,I2,I3: Points where piston at IDC
9550   !  Per: Period of engine cycle
9560   !  Cr: Compression ratio
9570   !  Ph: Specifies phase of data
9580   !  N: Number of waveforms averaged
9590   !  Rpm: Rev./min.
9600   !  Pw: Work of power loop
9610   !  Nw: Pumping losses
9620   !  Ntw: Net work of cycle
9630   !  Hp: Horsepower
9640   !  Imep: Indicated mean effective pressure
9650   !
9660   !Subprograms used:
9670   !  FNCalc_rpm: Returns rev./min.
9680   !  Work: Calculates Pw,Nw,Ntw (in ft.lbs.)
9690   !  FNHorsepower: Returns horsepower
9700   !  FNInd_mep: Returns IMEP
9710   !  Prnt: Prints results with optional
9720   !    hardcopy
9730   !
9740    OFF KEY 0
9750    OFF KEY 1
9760    OFF KEY 2
9770    OFF KEY 3
9780    OFF KEY 4
9790    Rpm=FNCalc_rpm(Per)
9800    CALL Work(A(*),I1,I2,I3,Pw,Nw,Ntw,Ph)
9810    Hp=FNHorsepower(Ntw,Per)
9820    Imep=FNInd_mep(A(*),Pw,I1,I2)
9830    CALL Prnt(Cr,N,Rpm,Pw,Nw,Ntw,Hp,Imep)
9840   SUBEND
```

Subroutine An is a calling subprogram that analyses the data to determine the work done by the cycle, indicated horsepower, and IMEP. It then calls Print to print the results on the computer screen and produce a hard copy if desired by the user.

Function FNCalc-rpm

```
10800  DEF FNCalc_rpm(Period)
10810  !Calculates rpm of engine
10820  !
10830  !Variables and constants used:
10840  !  Period: Period of engine cycle (secs.)
10850  !
10860   RETURN 60*2/Period
10870  FNEND
```

Function FNCalc-rpm calculates the rpm of the engine, based on the period, in seconds per cycle, of the engine.

Subroutine Work

```
7110   SUB Work(A(*),I1,I2,I3,Pw,Nw,Ntw,P)
7120   !This subroutine calculates the work
7130   !done by the engine cycle (in ft.lbs.)
7140   !
7150   !Variables and constants used:
7160   !  A: Array holding data
7170   !  I1,I2,I3: Points where piston at IDC
7180   !  Pw: Work done in upper or power loop
7190   !    of the diagram
7200   !  Nw: Pumping losses
7210   !  Ntw: Net indicated work done by entire
7220   !    cycle
7230   !  P: Phase of cycle used (P=1 if I1 at end
7240   !    of compression stroke, P=2 if I1 at
7250   !    end of exhaust stroke
7260   !  ODC1,ODC2: Points where piston at ODC
7270   !  Power_stroke,Exhaust_stroke,Intake_
7280   !    stroke,Compr_stroke: Work done
7290   !    during these strokes (ft.lbs.)
7300   !
7310   !Subprograms used:
7320   !  FNTrap: Returns integral under curve
7330   !    between two points using the
7340   !    Trapezoid method of numerical
7350   !    integration
7360   !
7370    !Find points at ODC
7380    Odc1=INT((I1+I2)/2)
7390    Odc2=INT((I2+I3)/2)
7400    !Use the trapezoid rule to calculate work
7410    ! done during four engine strokes
7420    IF P=1 THEN
7430     Power_stroke=FNTrap(A(*),I1,Odc1)/12
7440     Exhaust_stroke=FNTrap(A(*),Odc1,I2)/12
7450     Intake_stroke=FNTrap(A(*),I2,Odc2)/12
7460     Compr_stroke=FNTrap(A(*),Odc2,I3)/12
7470    END IF
7480    IF P=2 THEN
7490     Power_stroke=FNTrap(A(*),I2,Odc2)/12
7500     Exhaust_stroke=FNTrap(A(*),Odc2,I3)/12
7510     Intake_stroke=FNTrap(A(*),I1,Odc1)/12
```

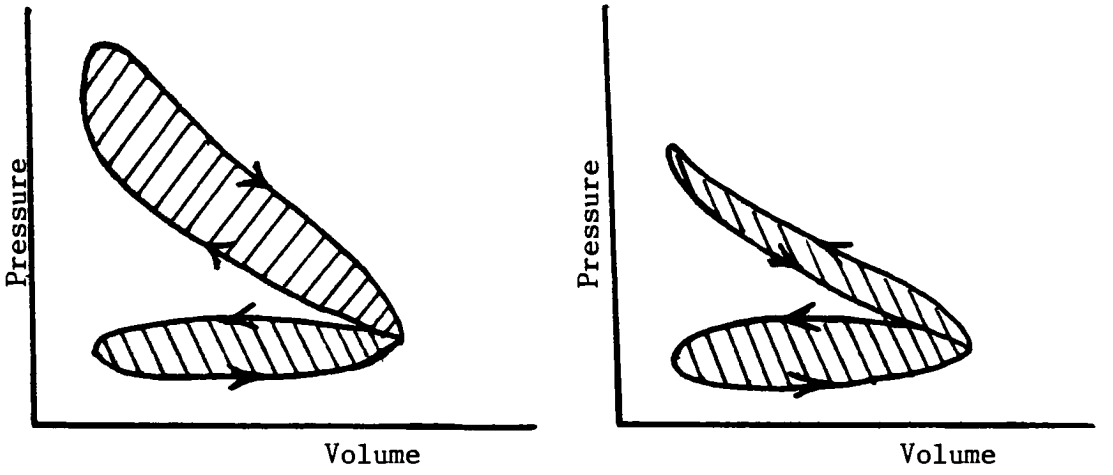
```
7520      Compr_stroke=FNTrap(A(*),Odc1,I2)/12
7530     END IF
7540     !Find net works
7550     Pw=Power_stroke+Compr_stroke
7560     Nw=Intake_stroke+Exhaust_stroke
7570     Ntw=Pw+Nw
7580    SUBEND
```

Subroutine Work calculates three types of work that can be determined from the indicator diagram. These works are defined as follows (refer to Fig. A2).

1. Positive Work: Area of the upper loop of the indicator diagram.
2. Negative Work: Area of the lower loop of the indicator diagram (valve losses).
3. Net Work: The sum of the above two.

It should be noted that these works are named according to the signs that they have when the engine is firing. "Positive Work" will be a positive number when the engine is firing, and the "Net Work" will be positive. When the engine is being motored (driven by the dynamometer), however, the "Positive Work" will be a negative number, and the "Net Work" will be negative. The "Negative Work" (valve losses) is always a negative quantity.

The area under the curve must be determined for each of the four engine strokes. Subroutine Work uses function FNTrap (see below) to return the numerical integration under each stroke process line. Processes that occur



a. Engine Firing

b. Engine Motored

//// positive work
\\\\ negative work

Fig.A2

Work Areas of Indicator Diagram
Firing and Motoring Modes

while the piston is traveling toward ODC in an indicator diagram are positive in sign and those that occur when the piston is moving toward IDC are negative. This simplifies the determination of the sign of the work for each process, since FNTrap returns values of the correct sign automatically according to the sign convention used here.

The first two lines of code in Work find the two data points in the waveform data which correspond to points where the piston is at approximately ODC. The segments of data which correspond to the various strokes must then be determined, based on the phase of the waveform. This is done by the IF/THEN/ELSE section of the subroutine, which can be understood by referring to Fig. A1.

Function FNTrap

```
7610   DEF FNTrap(A(*),Start,Finish)
7620   !This function returns the value of the
7630   !area under the data points, from point
7640   !"START" to point "FINISH". The TRAPEZIOD
7650   !method is used to evaluate th area
7660   !numerically.
7670   !
7680   !Variables and constants used:
7690   !  A: Array holding data points, with
7700   !     vertical coord. in first column and
7710   !     horizontal coord. in second column.
7720   !  Start,Finish: Row of first data point
7730   !     and last data point in interval
7740   !  Integral: Value of area under curve
7750   !     between Start and Finish
7760   !
7770    Integral=0
7780    FOR I=Start TO Finish-1
7790     Integral=(A(I,1)+A(I+1,1))*(A(I+1,2)-A(I,2))/2+Integral
7800    NEXT I
7810    RETURN Integral
7820   FNEND
```

Function FNTrap uses the trapezoid method to do a numerical integration on the data passed in array A between point Start and point Finish. It should be noted that, if Start is a higher number than Finish, as it would be when the piston is traveling from a large volume at ODC to a smaller one at IDC, the value of the integral returned will be negative.

Function FN Horsepower

```
7850   DEF FNHorsepower(Work,Per)
7860   !This function returns the horsepower for
7870   !the cycle, based on the work entered.
7880   !The work must be entered in ft.lbs.
7890   !
7900   !Variables and constants used:
7910   !  Work: Work output of cycle (ft.lbs.)
7920   !  Per: Period of engine cycle
7930   !  Hp: Horsepower
7940   !
7950    Hp=Work/(550*Per)
7960    RETURN Hp
7970   FNEND
```

This function returns the indicated horsepower delivered by the engine.

Function FNInd-mep

```
9870   DEF FNInd_mep(C(*),Work,I1,I2)
9880   !Calculates the indicated mean effective
9890   !pressure (IMEP). Work is input in ft.lbs.
9900   !and and volumes are input in in.**3.
9910   !IMEP returned in psi
9920   !
9930   !Variables and constants used:
9940   !  C: Array holding data
9950   !  Work: Work of power loop
9960   !  I1,I2: First two data points where
9970   !    piston at IDC
9980   !
9990   !Subprograms used: None
10000  !
10010   Imep=Work*12/(C((I1+I2)/2,2)-C(I1,2))
10020   RETURN Imep
10030  FNEND
```

Function FNInd-mep returns the indicated mean effective pressure (IMEP), in psi, using equation [6].

Subroutine Prnt

```
10060  SUB Prnt(Cr,N,Rpm,Pw,Nw,Netw,Hp,Imep)
10070  !Prints out the results of the analysis of
10080  !the data. A hardcopy is optional.
10090  !
10100  !Variables and constants used:
10110  !  Cr: Compression ratio
10120  !  N: Number of cycles averaged
10130  !  Rpm: Rev./min.
10140  !  Pw: Work of power loop
10150  !  Nw: Valve losses
10160  !  Netw: Net work of cycle
10170  !  Hp: Indicated horsepower output
10180  !  Imep: Indicated mean effective pressure
10190  !  Resp$: Input by user for hardcopy
10200  !
10210  !Subprograms used: None
10220  !
10230   DIM Resp$[1]
10240   FOR I=1 TO 18
10250    PRINT " "
10260   NEXT I
10270   PRINT "          RESULTS"
10280   PRINT " "
10290   PRINT "Engine speed:",INT(Rpm*100+.5)/100,"rpm"
10300   PRINT "Compression ratio:",Cr
10310   PRINT "Work:"
10320   PRINT "  Gross work output:",INT(Pw*100+.5)/100,"ft-lb"
10330   PRINT "  Valve loss:       ",INT(Nw*100+.5)/100,"ft-lb"
10340   PRINT "  Net work:         ",INT(Netw*100+.5)/100,"ft-lb"
10350   PRINT "Indicated horsepower:",INT(Hp*100+.5)/100,"hp"
10360   PRINT "IMEP:",INT(Imep*100+.5)/100,"psi"
10370   PRINT " "
10380   PRINT "Averaged over",N,"cycles"
10390   !Check if a hardcopy is desired
10400   INPUT "DO YOU WANT A HARDCOPY? (Y/N)",Resp$
10410   IF Resp$="Y" OR Resp$="y" THEN
10420    DUMP ALPHA #701
10430   END IF
10440   FOR I=1 TO 18
10450    PRINT " "
10460   NEXT I
10470  SUBEND
```

Subroutine Prnt (Printout) causes the analyzed results to be printed on the computer screen. One copy of the results is available each time this subroutine is called.

Subroutine Print-data

```
8000   SUB Print_data(A(*),First_pt,Last_pt)
8010   !This subroutine prints a hard copy of
8020   !the pressure, volume, and crank angle data
8030   !
8040   !Variables and constants used:
8050   !  A: Array holding data
8060   !  First_pt,Last_pt: First and alst points
8070   !    to be printed
8080   !  Respon$: User response to whether hard
8090   !    copy of data desired
8100   !
8110    DIM Respon$[1]
8120    OFF KEY 0
8130    OFF KEY 1
8140    OFF KEY 2
8150    OFF KEY 3
8160    OFF KEY 4
8170    FOR I=1 TO 18
8180     PRINT " "
8190    NEXT I
8200    PRINT "To stop data scroll, use PAUSE key."
8210    PRINT "To resume scroll, use CONTINUE key."
8220    FOR I=1 TO 5
8230     PRINT " "
8240    NEXT I
8250    WAIT 10
8260    PRINT " Pt        P(psia)  V(in**3)   Angle(deg.)"
8270    FOR I=First_pt TO Last_pt
8280     A(I,1)=INT(A(I,1)*100+.5)/100
8290     A(I,2)=INT(A(I,2)*100+.5)/100
8300     A(I,3)=INT(A(I,3)*100+.5)/100
8310     PRINT I,A(I,1),A(I,2),A(I,3)
8320    NEXT I
8330   PRINT "HARD COPY?"
8340   INPUT Respon$
8350   IF Respon$="Y" OR Respon$="y" THEN
8360    PRINTER IS 701
8370    PRINT " Pt       P(psia)  V(in**3)  Angle(deg.)"
```

```
8380     FOR I=First_pt TO Last_pt
8390      PRINT I,A(I,1),A(I,2),A(I,3)
8400     NEXT I
8410     PRINTER IS 1
8420     ELSE
8430      SUBEXIT
8440     END IF
8450    SUBEND
```

Print-data produces a hard copy of the modified data as follows:

Datapoint: Pt

Pressure: P (psia)

Volume: V(in^3)

Crank angle: Angle (deg.)

All data points in one engine cycle are listed.

APPENDIX D

SETTING UP THE INDICATOR DIAGRAM GENERATION EQUIPMENT

The following instructions deal with the setting up of the equipment for generating indicator diagrams. The instructions consist of selections for setting up the three major sub-systems, digital (computer, oscilloscope, etc.), oscilloscope, etc.), pressure measurement, volume measurement (shaft encoder).

DIGITAL SYSTEM

The digital components of the system are as follows:

Digitizing oscilloscope:	Tektronix, model 2430
Desktop computer:	Hewlett-Packard, model 982G
Thermal printer:	Hewlett-Packard, model 2671G
HPIB cable:	Hewlett-Packard HP10833 (A or B)
HPIB cable:	Hewlett-Packard HP10631 (A or B)
2 10X oscilloscope probes:	Tektronix, model TEK PG133

Setting up the components of the digital system is simple. The steps are listed below.

1. Connect the printer to the port labeled "SELECT CODE 7" on the back of the computer using the HP10631 cable.
2. Connect the oscilloscope GPIB port on the back of the scope to the same computer port (SELECT CODE 7) as the printer by stacking the cable terminals at the computer port. Use the HP10833 cable for this.
3. Attach the scope probes to the CH1 and CH2 ports on the front of the oscilloscope. Make sure that the probes are properly set up with a retractable hook probe tip and an alligator ground tip on each to assure proper contact.

   With the oscilloscope probes set up as described above, the scope can be used as a voltmeter. It is convenient to use the scope to measure the excitation voltage for the shaft encoder when you get to that section below.
4. The last thing that must be done is to set up the oscilloscope output GPIB so that it will be able to communicate effectively with the computer. To accomplish this, turn on the scope and allow it to go through its startup sequence. Then perform the following three steps:

   - Press the "OUTPUT" button on the front of the scope. The output menu will be displayed on the bottom of the scope screen. Press the button on the screen bevel under SETUP. Now the setup menu is on the screen. Press the button under TERM (stands for terminator) to get to the next menu level. Now press the button

under LF/EOI so that this selection is underlined. You have now set the scope to look for linefeed and end-of-line characters as line terminators in commands from the computer.

- Press the "OUTPUT" button again on the front of the scope. This returns you to the first level of the output menu. Now press the button under SETUP, and then the button under MODE on the menu display. Select T/L (Talk/Listen) from the MODE menu.
- Press the "OUTPUT" button once more, then SETUP, and select ADDR (address) from the setup menu to set the address of the scope with respect to the computer. Set the address, displayed on the screen, to 12 by pressing the buttons under the arrows. Pressing the button under the arrow pointing up increases the address number, and pressing the arrow under the arrow pointing down decreases it.

The scope can be turned off now, if desired, since it will store the settings just made until they are changed by the user.

PRESSURE MEASUREMENT SYSTEM

The pressure measurement system consists of the following components:

Piezo-electric pressure transducer: Kistler model 7061

Charge amplifier: Kistler model 504A/36

Cooling water apparatus for pressure transducer

Output lead for pressure transducer: Buel and Kjaer No. A00038

Output lead for charge amplifier: RNC to alligator, cable type RG58 A/U

Torque wrench (Micro-torque recommended) with 9/16 in deep socket

The first part of this system to check is the transducer cooling water circulation apparatus. This apparatus should be set up as shown in Fig. 9, Components section. Both reservoirs must be more than half full of distilled water to allow for maximum heat transfer without significant increase of the water temperature. Check the water level in both reservoirs. If either reservoir is less than half full, add more distilled water to the lower reservoir. Then pump the water to the upper, if that reservoir is low, by running the circulation pump. If the cooling water appears dirty or the lids have been left off the reservoirs, empty the water from the apparatus, rinse, reassemble the system, and then add fresh distilled water to the lower reservoirs while the pump is running until the proper levels are reached in both reservoirs. ONLY distilled water should be used so that mineral deposits do not develop in the pressure transducer. Make sure that the reservoir lids are always firmly in place so that the water is not contaminated.

Check the water lines for the transducer cooling carefully, making sure that they do not touch surfaces of the engine, such as the exhaust pipe, that will become hot. Also, check that the lines are not positioned near moving parts of the engine such as the flywheel or the magnito coupling.

Once the transducer cooling water apparatus has been set up and checked as explained above, the rest of the pressure measurement system can be assembled as outlined below.

1. Use the torque wrench, set to 221 in.-lb., with the 9/16 in. deep socket to torque the pressure transducer into the port opposite the sparkplug in the engine cylinder.
2. The transducer sensitivity should be set on the front of the charge amplifier to 5.27 pC/psi. Set the charge amplifier sensitivity to 50 psi/Volt and the time constant to LONG.
3. Attach one end of the B and K No. A00038 cable to the output of the pressure transducer. Attach the other end of the cable to the "INPUT" port on the back of the charge amplifier. In order to minimize electrical noise in the transducer output, make sure that this cable does not rest on any other live electrical wires.
4. Connect up the cooling water lines to the pressure transducer by attaching the 1/8 in. sections of Tygon tubing to the two barbed fittings on the transducer.
5. Attach the BNC end of the RG58 A/U cable to the output port on the back of the charge amplifier. The alligator clips at the other end of the cable should be connected to the Ch2 probe of the oscilloscope, making sure that the polarity is correct.

SHAFT ENCODER SYSTEM

The shaft encoder and peripherals are listed below.

Optical Incremental Encoder and connector: Sequential Information Systems, Inc. model 25GN-2IZ-5V-H1-D1-B3-T1

Power Supply: HP model 6236B

Banana-to-Alligator leads (2)

The basic setup of the shaft encoder system will now be given, followed by instructions for checking the alignment of the output of the encoder with the crank angle. If the alignment is found to be incorrect, the directions for correcting the alignment are included. These directions for correcting the alignment of the encoder would also be of use when installing the encoder after removing it from the shaft for any reason.

Setup of Basic Shaft Encoder System

Following is a description of the setup of the shaft encoder system. It involves applying the excitation voltage to the encoder and connecting the output leads from the encoder to the oscilloscope.

1. Insert the banana ends of the banana-to-alligator leads into the +6V and COMMON ports of the power supply. Set the METER knob to +6V, then turn the VOLTAGE +6V knob under the METER knob to its extreme counter-clockwise position.
2. Five (5±.25V) Volts excitation must be applied to the shaft encoder. The level of the power supply output can be checked by using a voltmeter of sufficient accuracy or by using the horizontal scale of the oscilloscope.

to use the oscilloscope, attach the leads from the power supply to the Chl scope probe. Set Chl Volts/Div. to 2 Volts/div, and the Sec/Div to 5 ns/div. Select the AUDIO trigger mode by pressing the trigger MODE button positioned toward the left on the face of the scope. The MODE menu will now be displayed on the screen. Press the button under AUTO on the screen display to select that trigger mode from the menu.

3. Now turn on the power supply and adjust its output by using the +6 Volt knob until the vertical display on the scope shows +5 Volts (±.25 V).
4. Turn the power source off and then detach the scope probe from the source leads.
5. Attach the scope and power source leads to the shaft encoder leads as follows:

   - +6 V lead from power source to red wire from shaft encoder (labeled "+ EXCITATION").
   - Common lead from power source to black wire from shaft encoder (labeled "GROUND (EXCITATION AND INDEX)").
   - Main probe lead (grey) from Chl) of the scope to white wire from shaft encoder (labeled "ZERO INDEX OUTPUT").
   - Reference scope probe lead (black) from Chl of the scope to black wire, mentioned above, from shaft encoder.

6. Now turn on the power source. The shaft encoder system is now set up so that the encoder output is displayed on the scope screen, and you are

ready to go to the next section to check the alignment of the encoder with the engine crank angle.

Checking the Alignment of the Shaft Encoder

In order to determine the alignment of the encoder with the crank angle of the engine shaft, the system must first be set up as described in the section above. The encoder output is compared with the crank angle that is marked on the large flywheel on the drive shaft. The degrees marked on the flywheel are referenced by the metal pointer that is mounted above the wheel on the engine, so that the piston is at top dead center when 0 deg. is positioned under the pointer. Check the alignment of the encoder as follows:

1. Set up the encoder system as described in the section above.
2. Rotate the flywheel in the direction of increasing degrees (clockwise when looking at the wheel from the dynamometer end of the shaft) until the encoder signal goes from low to high as observed on the scope screen. This should take place less than 3 deg. from 0 deg. on the flywheel.
3. If the encoder is not aligned properly with the crank angle, adjustment is necessary as described in the next section.

Adjusting Shaft Encoder Alignment

This section details the procedure used to align the shaft encoder properly with the crank angle. Before proceeding, you should keep in mind

that the encoder is rated for maximum loadings of 40 lbs. axially and 35 lbs. radially. Any forces applied to the encoder shaft should be well below these values, or the inner mechanism of the encoder will be damaged.

1. Remove the four screws on the mounting flange of the encoder. Loosen the setscrew on the flexible coupling. Gently withdraw the encoder shaft and fitting from the flexible coupling, being careful not to lose the key between the fitting and the coupling.
2. Loosen the two setscrews in the fitting, and rotate the fitting on the encoder shaft to a position where it would likely produce a correctly aligned output. Tighten the setscrews until snug.
3. Gently insert the encoder shaft, fitting and key into the flexible coupling, and replace the four mounting flange screws.
4. Test the encoder alignment again using the scope display.
5. Repeat the above four steps until the encoder alignment is within acceptable limits. When alignment is attained, tighten the setscrew on the flexible coupling until just snug.

APPENDIX E

RUNNING THE INDICATOR DIAGRAM GENERATION EQUIPMENT

After the indicator diagram generation system has been set up as described in the section "Setting up the Indicator Diagram Equipment", you are ready to run the equipment and generate diagrams. The procedure for running the system, while the engine is in spark ignition mode, follows.

1. Turn on the indicator diagram generation equipment (computer, printer, oscilloscope, cooling water pump for pressure transducer, charge amplifier, and power supply). Be especially careful to turn on the cooling water pump for the pressure transducer and open the valve in that system, since the transducer must be cooled constantly while the engine is running. When turned on, a message will appear on the computer asking which language, B or H, is desired. Do not respond, and the system will default to Basic (B).
2. Start the Ricardo engine, following the "Starting the Engine" and "Running the Engine" sections of "Ricardo Operating Instructions: Spark Ignition running". Adjust the carburetor valves and the spark angle until the engine is running smoothly. The engine should be running at an almost constant rpm.

3. Insert the disc containing the program "IND" in the disc drive of the computer. Type GET "IND" and then the EXECUTE key. The program will be loaded, and while this is happening the LED next to the drive door will flash.
4. When the LED stops flashing, press the RUN key on the computer. A set of basic equipment set up instructions will appear on the computer screen. After checking that these have been complied with, press the CONTINUE key. Enter the crank angle degree at which the shaft encoder output goes high as instructed in the next prompt. Value can be read from the degrees marked on the engine flywheel. The blocks at the bottom of the screen correspond to the "soft keys", labeled k0 through k9, located above the character keyboard on the computer. Pressing the soft keys causes the following to be performed by the program:

   GET DATA: Data is acquired and modified to units of pressure, volume, and crank angle. Requires input by user of compression ratio, charge amplifier Range setting, and number of cycles to be averaged.

   PLOT P-V: Plots indicator diagram. User inputs "P" from keyboard for hardcopy of plot and "Q" to exit program segment.

   ANALYZE: Calculates and displays indicated work, indicated horsepower, and IMEP. User inputs "Y" from keyboard for hardcopy of results and "N" to exit program segment.

HC DATA: Produces hardcopy of modified data (pressure, volume, and crank angle) for one engine cycle.

END: Causes program exit.

5. The GET DATA soft key must be used first, since obviously data must be taken before it can be plotted or analyzed.
6. Press the GET DATA soft key (k0). You will now be prompted to input three values needed by the program, the engine compression ratio, the charge amplified Range setting, and the number of engine cycles to be averaged. You must press the CONTINUE key after each response. After inputting values, the program requests confirmation. If your input value is correct, enter "Y" of "y", then press CONTINUE.
7. Now the program begins data acquisition and displays "GATHERING DATA" on the screen. When finished, "DATA GATHERING COMPLETE" is printed on the screen.
8. You may select from any of the soft keys at this point. If GET DATA is selected, the compression ratio, range setting, and number of cycles to be averaged must be entered again. Remember that the CONTINUE key must be pressed after each input by the user in all program segments.
9. When finished with the program, press the END soft key to exit the program or just turn off the computer.
10. Turn off the Ricardo engine, following the instructions in the "Stopping the Engine" section of "Ricardo Operating Instructions: Spark Ignition Running".
11. Disassemble the diagram generation equipment. The cooling water should be allowed to circulate through the pressure transducer for as

long as possible, so unplug the circulation pump and turn off the valve for this system last. The pressure transducer can be left in place in the sparkplug hole of the engine if the system will be used again soon. If the transducer will not be used again soon, however, it is best to remove the transducer and replace with the plug provided. The pressure transducer has a finite lifetime, and it is best to remove it after use so that no one runs the engine with the transducer in place and its cooling water system off. The shaft encoder can be left in place.

APPENDIX F

MOTORING DATA USED TO INVESTIGATE PRESSURE/CRANK ANGLE PHASING

Ascending rpm		Descending rpm	
rpm	Angle of Max Press. (deg.)	rpm	Angle of Max Press. (deg.)
202.02	2.42	199.67	2.40
303.03	0.00	300.75	3.61
394.74	3.32	406.50	3.90
500.00	4.80	510.20	4.90
603.62	5.07	601.20	5.05
705.05	6.77	705.88	6.78
811.91	8.77	797.87	7.66
900.90	8.65	904.98	8.69
996.68	7.18	1015.23	8.53
1102.94	9.26	1117.32	9.39
1156.07	9.71	1212.12	13.09
1310.04	12.18	1315.79	13.42
1398.60	13.84	1405.15	13.49
1515.15	14.10	1518.99	13.67
1587.30	15.72	1623.82	15.59
1694.92	16.27	1719.20	16.50
1826.48	17.53	1804.51	17.32
1923.08	18.46	1916.93	18.98
1990.05	17.91	1993.36	17.94
2112.68	20.28	2097.90	19.50
2247.19	20.22	2189.78	21.70
2312.14	22.84	2303.26	21.40
2489.63	22.41	2464.07	25.13
2702.70	24.32		

APPENDIX G

CALCULATIONS FOR COMPARISON OF AIR STANDARD OTTO CYCLE AND ACTUAL RESULTS TAKEN AT 20 DEGREES SPARK ADVANCE

Determination of Energy Ideally Added by Fuel per Cycle:

Table A1

Volumetric Flowrate of Fuel

Data Point	Fuel Level (ml)		Time min/sec	Flowrate (cc/sec)
	Initial	Final		
1	102	55	4/0.0	0.1958
2	80	11	5/53.8	0.1950
3	97	10	7/33.2	0.1920
4	96	28	5/41.5	0.1991
5	96	10	6/23.6	0.2242
6	85	2	7/13.2	0.1916
7	100	7	8/60.0	0.1726
8	99	4	11/45.0	0.1348
9	92	2	7/49.2	0.1918
10	40	6	2/55.8	0.1934

mean: 0.189 cc/sec

(Above data taken at 1360 rpm, spark advance of 20 degrees, etc., under same conditions and directly after generating results at 20 degrees spark advance in Appendix F)

Heat of Combustion of octene: 19,035 Btu/lbm
Specific Gravity of octene: 0.702

flowrate of octene:

$$0.1890 \text{ cc/sec } \left(\frac{m^3}{10^6 \text{ cc}}\right)\left(\frac{1000 \text{ kg}}{m^3}\right)(0.702)\left(\frac{1 \text{ lbm}}{0.4536 \text{ kg}}\right)$$

$$= 2.925 \times 10^{-4} \text{ lbm/sec}$$

$$19{,}035 \text{ Btu/lbm } (2.925 \times 10^{-4} \text{ lbm/sec})\left(\frac{1 \text{ ft.lb}}{1.285 \times 10^{-3} \text{ Btu}}\right)$$

$$\left(\frac{1 \text{ min}}{1360 \text{ rev}}\right)\left(\frac{60 \text{ sec}}{1 \text{ min}}\right)\left(\frac{2 \text{ rev}}{1 \text{ cycle}}\right)\left(\frac{12 \text{ in}}{1 \text{ ft}}\right)$$

$$= 4{,}588.4 \text{ in.lb/cycle} \quad (Q \text{ from octene})$$

Determination of State Values and 1st Law Chart for Air Standard Cycle

Table A2

State Values of Air Standard Cycle

Point	p (psia)	T (°R)	V (in³)	U (in.lb)
1	14.7	530.0	34.791	1276.6
2	318.6	1276.3	3.866	3074.4
3	794.0	3181.1	3.866	7662.8
4	36.6	1321.0	34.791	3182.0

Table A3

First Law Chart for Air Standard Cycle

Points	Process	$\int \delta Q$ (in.lb)	$\int dU$ (in.lb)	$\int \delta W$ (in.lb)
1-2	$S = S_1$	0.0	1797.7	-1797.7
2-3	$V = V_2$	4588.4	4588.4	0.0
3-4	$S = S_3$	0.0	-4480.7	4480.7
4-1	$V = V_4$	-1905.4	-1905.4	0.0

Properties of air:

$$C_v = 1597.8 \frac{\text{in.lb}}{\text{lbm.}^\circ\text{R}}$$

$$R = 640.08 \frac{\text{in.lb}}{\text{lbm.}^\circ\text{R}}$$

Pt.1:

$p = 14.7$ psia

$V = 34.791$ in^3

$T = 70^\circ\text{F} = 530^\circ\text{R}$

$$p_1 V_1 = mRT_1$$

$$m = \frac{p_1 V_1}{R T_1} = \frac{(14.7)(34.791)}{(640.08)(530)} = 1.5076 \times 10^{-3} \text{ lbm}$$

$$U_1 = C_v T_1 m = (1597.8)(530)(1.5076 \times 10^{-3}) = 1276.6 \text{ in.lb}$$

Pt.2:

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$$

$$P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} = 14.7\left(\frac{34.791}{3.866}\right)^{1.4} = 318.57 \text{ psia}$$

$$T_2 = \frac{P_2 V_2 T_1}{P_1 V_1} = \frac{(318.57)(3.866)(530)}{(14.7)(34.791)} = 1276.31°R$$

$${}_1U_2 = C_v m(T_2 - T_1) = 2.4088(1276.3-530) = 1797.7 \text{ in.lb}$$

$${}_1Q_2 = {}_1U_2 + {}_1W_2$$

$$0.0 = 1797.7 + {}_1W_2$$

$${}_1W_2 = -1797.7 \text{ in.lb}$$

$$U_2 = U_1 + {}_1U_2 = 1276.7 + 1797.7 = 3074.4 \text{ in.lb}$$

Pt.3:

$${}_2Q_3 = {}_2U_3 = 4588.4 \text{ in.lb} \qquad \text{(from combustion of octene)}$$

$$U_3 = U_2 + {}_2U_3 = 3074.4 + 4588.4 = 7662.8 \text{ in.lb}$$

$$U_3 = C_v m T_3$$

$$T_3 = \frac{U_3}{C_v m} = \frac{7662.76}{2.4088} = 3181.1°R$$

$$P_3 = \frac{mRT_3}{V_3} = \frac{(1.50756\times10^{-3})(640.08)(3181.5)}{3.866} = 794.0 \text{ psia}$$

$${}_2W_3 = 0.0$$

Pt.4:

$$p_4 = p_3\left(\frac{V}{V}3_4\right)^{\gamma} = 794.02\left(\frac{3.866}{34.791}\right)^{1.4} = 36.639 \text{ psia}$$

$$T_4 = \frac{p_4 V_4}{mR} = \frac{(36.639)(34.791)}{(1.508\times10^{-4})(640.08)} = 1321.0°R$$

$$U_4 = C_v m T_4 = (2.4088)(1321.0) = 3182.0 \text{ in.lb}$$

$$_3U_4 = U_4 - U_3 = 3182.02 - 7662.76 = -4480.74 \text{ in.lb}$$

$$_3Q_4 = {}_3U_4 + {}_3W_4$$

$$0.0 = -4480.74 + {}_3W_4$$

$$_3W_4 = 4480.74 \text{ in.lb}$$

pts.4 - 1

$$_4U_1 = C_v m(T_1 - T_4) = 2.4088(530-1321) = -1905.4 \text{ in.lb}$$

$$_4Q_1 = {}_4U_1 + {}_4W_1 = -1905.4 + 0.0 = -1905.4 \text{ in.lb}$$

Calculations for Comparison of Actual and Air Standard Cycle Results Shown in Table III:

Actual Cycle:

$$\eta_t = \frac{\oint \delta W}{{}_2Q_3} = \frac{171.59 \text{ ft.lb}}{382.37 \text{ ft.lb}} = 44.8\%$$

from eq'n [3], based on power loop only

$$\eta_m = \frac{BMEP}{IMEP} = \frac{bhp}{ihp} = \frac{2.06}{3.22} = 63.1\%$$

from eq'n [12]

Air Standard Cycle:

$$\eta_t = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{9^{1.4-1}} = 58.5\%$$

from eq'n [5]

$$\oint \delta W = {}_1W_2 + {}_2W_3 + {}_3W_4 + {}_4W_1 = -1797.7 + 0.0 +$$

$$4480.7 + 0.0 = 2683.0 \text{ in.lb} = 223.6 \text{ ft.lb}$$

$$IMEP = \frac{\oint \delta W}{V_1 - V_2} = \frac{2683.0}{34.791 - 3.866} = 86.76 \text{ psia}$$

from eq'n [6]

APPENDIX H

ERROR ANALYSIS OF ACTUAL RESULTS

The percent error in X, with a relation of the following form:

$$X = \frac{A\ B^m}{C^n}$$

where A,B, and C are independent variables, can be written as

$$\left|\frac{\Delta X}{X}\right| = \left|\frac{\Delta A}{A}\right| + \left|\frac{m\Delta B}{B}\right| + \left|\frac{n\Delta C}{C}\right| \qquad [13]$$

where ΔA, ΔB, and ΔC are errors in A,B,and C (see ref.9, pg.270).

Work is calculated in the computer software using the Trapezoid rule, or

$$W = \frac{1}{2}\ p\ V_{int} \qquad [14]$$

where V_{int} is the width of the volume interval. In order to calculate the percent error in work, therefore, the percent errors in pressure and volume measurements must be determined. These determinations will be shown in the following sections.

Error in Volume

Cylinder volume can be written as (see Fig.A3 for definitions of variables)

$$V = \frac{\pi}{4} D^2 h$$

so that

$$\frac{\Delta V}{V} = \left| \frac{2\Delta D}{D} \right| + \left| \frac{\Delta h}{h} \right| \qquad [15]$$

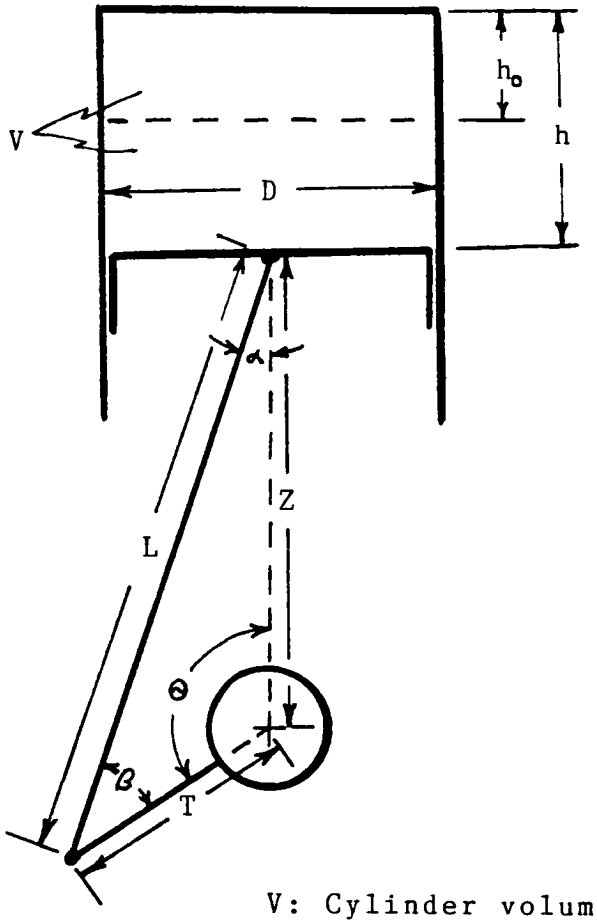
Measurements D,L, and T are assumed to be accurate to 0.001 in. and are as follows:

$$D = 3.000 \pm 0.001 \text{ in.}$$
$$L = 9.500 \pm 0.001 \text{ in.}$$
$$T = 2.188 \pm 0.001 \text{ in.}$$

The quantities above effect the value of h as does the value of the crank angle, θ. The error in θ arises from the following sources:

- ± 0.5 degrees: from reading the flywheel
- ± 2.901 degrees: from three standard deviations of the angle correction formula discussed in the Evaluation of Motoring Data section.
- ± 0.5 degrees: from possible error in the theory behind above mentioned angle correction formula

The total error in θ can therefore be taken as ± 3.901 deg.



V: Cylinder volume
D: Cylinder inner diameter
h: Cleared height
h_o: Hieght of clearance volume
L: Rod length
T: Throw length
Z: Length as shown
Θ: Crank angle
α,β: Angles as shown

Fig.A3

Schematic of Engine Geometry

In order to determine h_0, the compression ratio, r, must be known. Here, the compression ratio will be taken as 9.00, since this is the ratio used when gathering data in this report. The stroke, S, of the Ricardo engine is 4.375 inches. The value of h_0 can now be calculated.

$$h_0 = \frac{1}{r-1} S = \frac{1}{9-1} (4.375) = 0.547 \text{ in.}$$

The error in h due to the error in θ will be evaluated here, since the percent error in L and T is relatively small (less than .001 for L and T compared to .011 for θ). The error in h at three different values of θ will now be determined.

$\underline{\theta = 0°}$: $h = h_0 = 0.547$ in.

$\theta = 0° + \Delta\theta = 0 + 3.901 = 3.901°$

Using the Law of Sines,

$$\frac{T}{\sin\alpha} = \frac{L}{\sin\theta}$$

so that

$$\alpha = \sin^{-1}\left(\frac{T}{L}\sin\theta\right) = \sin^{-1}\left(\frac{2.188}{9.500}\sin 3.901\right) = 0.898°$$

$$\beta = 180° - 0 - \quad = 180 - 3.901 - 0.898 = 175.201°$$

$$\frac{Z}{\sin\beta} = \frac{L}{\sin\theta}$$

so that

$$Z = L\frac{\sin\beta}{\sin\theta} = 9.500\,\frac{\sin 175.201}{\sin 3.901} = 11.682 \text{ in.}$$

$$h = h_o + L + T - Z = 0.547 + 9.500 + 2.188 - 11.682$$
$$= 0.553 \text{ in.}$$
$$\Delta h = 0.553 - 0.547 = 0.006 \text{ in.}$$

Therefore, the percent error at $\theta = 0°$ is

$$\frac{\Delta h}{h} = \frac{0.006}{0.547} = 0.011$$

Similarly,

$$\theta = 90°: \quad \frac{\Delta h}{h} = \frac{0.148}{2.990} = 0.049$$

$$\theta = 180°: \quad \frac{\Delta h}{h} = \frac{0.002}{4.922} = 0.0005$$

As can be seen from above, the effect of the error in θ on the percent error in h is greatest at $\theta = 90°$. This is to be expected, since the piston travels farther at $\theta = 90°$ and $\theta = 270°$ for each increment in shaft rotation than at any other value of θ. The percent error in h at $\theta = 90°$ will, therefore, be used below.

Using equation [15],

$$\frac{\Delta V}{V} = \frac{2(0.001)}{3.000} + 0.049 = 0.001 + 0.049 = 0.050 \text{ or } 5.0\%$$

Error in Pressure

The error in the pressure measurement is due to the limits in the digitizing of the oscilloscope, since

the error due to the pressure transducer itself is very small when the transducer is water cooled. The scope digitizes using 8 bits, or a 1 in 256 resolution. The percent error in pressure measurement is, therefore,

$$\frac{\Delta p}{p} = \frac{1}{256} = 0.004 \text{ or } 0.4\%$$

Now, to determine the percent error in, equation [14] is put in the form of equation [13] so that

$$\frac{\Delta W}{W} = \frac{\Delta p}{p} + \frac{\Delta V}{V} = 0.004 + 0.050 = 0.054 \text{ or } 5.4\%$$

It should be noted that the percent error in work calculated above would also be the error in the indicated horsepower, since the period of the engine cycle is measured very accurately by the system.

In order to determine the error in IMEP, we must start with the following relation (ref.9,pg.269):

$$\Delta f = \left|\Delta A \frac{\partial f}{\partial A}\right| + \left|\Delta B \frac{\partial f}{\partial B}\right| + \left|\Delta C \frac{\partial f}{\partial C}\right| + \cdots \quad [16]$$

where f is a function of the independent variables A, B, C, etc.. Equation [6], determining IMEP, is

$$\text{IMEP} = \frac{\int \delta W}{V_1 - V_2}$$

If V_1 and V_2 are considered independent variables, the error in IMEP can be written, according to equation [16], as

$$\Delta IMEP = \left|\Delta W \frac{\partial IMEP}{\partial W}\right| + \left|\Delta V_1 \frac{\partial IMEP}{\partial V_1}\right| + \left|\Delta V_2 \frac{\partial IMEP}{\partial V_2}\right|$$

$$= \left|\Delta W \frac{1}{V_1-V_2}\right| + \left|\Delta V_1 \frac{W}{(V_1-V_2)^2}\right| + \left|\Delta V_2 \frac{W}{(V_1-V_2)^2}\right|$$

W has been substituted in the above relation for $\int \delta W$. Dividing both sides by equation 6 , we obtain an equation for the percent error in IMEP, or

$$\frac{\Delta IMEP}{IMEP} = \left|\frac{\Delta W}{W}\right| + \left|\frac{\Delta V_1}{V_1-V_2}\right| + \left|\frac{\Delta V_2}{V_1-V_2}\right| \qquad [17]$$

We now must find V_1 and V_2 as follows:

$$V = \frac{\pi}{4} D^2 h$$

and

$$\frac{\partial V}{\partial h} = \frac{\pi}{4} D^2$$

$$\frac{\partial V}{\partial D} = 2 \frac{\pi}{4} D h$$

The error in V, using equation [16] is

$$\Delta V = \frac{\pi}{4} D^2 \Delta h + 2 \frac{\pi}{4} Dh\Delta D = \frac{\pi}{4} D (D\Delta h + 2h\Delta D) \qquad [18]$$

V_1 and V_2 are the cylinder volumes at $\theta = 180°$ and $\theta = 180°$, respectively. Therefore the previously determined values of Δh and h can be used. By equation [18],

$$\Delta V_1 = \frac{\pi}{4}(3.000)\left[3.000(0.002) + 2(4.922)(0.001)\right]$$

$$= 0.037 \text{ in.}$$

$$\Delta V_2 = \frac{\pi}{4}(3.000)\left[3.000(0.006) + 2(0.547)(0.001)\right]$$

$$= 0.045 \text{ in.}$$

also,

$$V_1 - V_2 = \frac{\pi}{4} D^2 S = \frac{\pi}{4}(3.000)^2(4.375) = 30.925 \text{ in.}$$

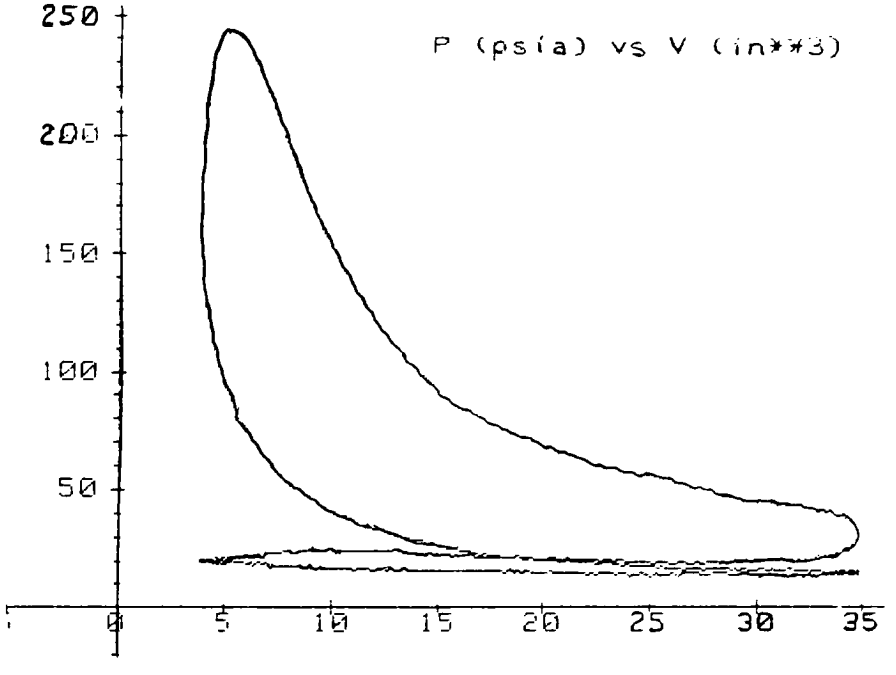
By equation [17],

$$\frac{\Delta IMEP}{IMEP} = 0.054 + \frac{0.037}{30.925} + \frac{0.045}{30.925} = 0.056 = 5.7\%$$

APPENDIX I

SAMPLE RESULTS

Complete Results at 20 Degrees Spark Advance:



RESULTS

Engine speed:	1360.54	rpm
Compression ratio:	9	
Work:		
Gross work output:	171.59	ft-lb
Valve loss:	-15.4	ft-lb
Net work:	156.19	ft-lb
Indicated horsepower:	3.22	hp
IMEP: 66.59	psi	
Averaged over	20	cycles

Pt.	P(psia)	V(in**3)	Angle(deg.)
84	169.9	3.87	359.29
85	173.3	3.87	.4
86	176.9	3.87	.91
87	180.9	3.87	1.73
88	183.7	3.88	2.55
89	186.5	3.89	3.36
90	190.1	3.91	4.18
91	193.7	3.92	5
92	196.9	3.95	5.81
93	201.1	3.97	6.63
94	203.5	4	7.45
95	206.9	4.03	8.26
96	210.3	4.06	9.08
97	214.1	4.1	9.89
98	216.3	4.14	10.71
99	220.1	4.18	11.53
100	222.7	4.22	12.34
101	224.5	4.27	13.16
102	227.9	4.32	13.98
103	229.7	4.38	14.79
104	231.9	4.44	15.61
105	234.5	4.5	16.43
106	235.7	4.56	17.24
107	238.3	4.63	18.06
108	239.9	4.7	18.87
109	240.9	4.77	19.69
110	242.7	4.85	20.51
111	243.3	4.92	21.32
112	244.7	5.01	22.14
113	244.9	5.09	22.96
114	244.9	5.18	23.77
115	244.9	5.27	24.59
116	245.3	5.36	25.4
117	243.1	5.46	26.22
118	243.1	5.56	27.04
119	242.1	5.66	27.85
120	241.1	5.76	28.67
121	240.1	5.87	29.49
122	238.3	5.98	30.3
123	237.1	6.09	31.12
124	234.1	6.21	31.94
125	232.7	6.32	32.75
126	229.5	6.44	33.57
127	227.5	6.57	34.38
128	224.9	6.69	35.2
129	221.7	6.82	36.02
130	219.1	6.95	36.83
131	215.7	7.09	37.65
132	213.5	7.22	38.47

133	208.9	7.36	39.28
134	205.9	7.5	40.1
135	202.3	7.64	40.91
136	199.9	7.79	41.73
137	195.7	7.94	42.55
138	192.3	8.09	43.36
139	188.1	8.24	44.18
140	185.1	8.39	45
141	181.3	8.55	45.81
142	178.7	8.71	46.63
143	174.9	8.87	47.45
144	171.5	9.03	48.26
145	167.3	9.2	49.08
146	164.5	9.37	49.89
147	160.9	9.54	50.71
148	157.9	9.71	51.53
149	155.3	9.88	52.34
150	152.3	10.06	53.16
151	148.3	10.23	53.98
152	145.3	10.41	54.79
153	142.1	10.59	55.61
154	140.3	10.78	56.43
155	137.5	10.96	57.24
156	134.5	11.15	58.06
157	131.7	11.34	58.87
158	128.3	11.52	59.69
159	125.7	11.72	60.51
160	123.5	11.91	61.32
161	120.9	12.1	62.14
162	118.7	12.3	62.96
163	115.7	12.49	63.77
164	114.1	12.69	64.59
165	111.5	12.89	65.4
166	109.3	13.09	66.22
167	107.5	13.3	67.04
168	105.5	13.5	67.85
169	103.3	13.7	68.67
170	102.5	13.91	69.49
171	99.9	14.12	70.3
172	98.9	14.32	71.12
173	96.9	14.53	71.94
174	95.1	14.74	72.75
175	92.7	14.95	73.57
176	90.1	15.17	74.38
177	89.7	15.38	75.2
178	87.7	15.59	76.02
179	86.1	15.81	76.83
180	84.7	16.02	77.65
181	84.3	16.24	78.47
182	83.5	16.45	79.28
183	82.1	16.67	80.1

184	81.7	16.89	80.91
185	80.7	17.1	81.73
186	78.7	17.32	82.55
187	78.1	17.54	83.36
188	77.3	17.76	84.18
189	75.9	17.98	85
190	75.5	18.2	85.81
191	73.7	18.42	86.63
192	73.5	18.64	87.45
193	72.9	18.86	88.26
194	72.1	19.08	89.08
195	71.7	19.3	89.89
196	70.7	19.52	90.71
197	69.7	19.74	91.53
198	68.3	19.96	92.34
199	67.7	20.18	93.16
200	68.1	20.4	93.98
201	66.3	20.62	94.79
202	65.5	20.84	95.61
203	65.5	21.06	96.43
204	64.3	21.28	97.24
205	64.3	21.5	98.06
206	63.5	21.71	98.87
207	62.7	21.93	99.69
208	62.1	22.15	100.51
209	61.3	22.36	101.32
210	60.3	22.58	102.14
211	60.1	22.79	102.96
212	58.7	23.01	103.77
213	59.1	23.22	104.59
214	58.7	23.44	105.4
215	58.1	23.65	106.22
216	57.7	23.86	107.04
217	56.9	24.07	107.85
218	57.1	24.28	108.67
219	55.5	24.49	109.49
220	56.1	24.69	110.3
221	56.1	24.9	111.12
222	56.1	25.1	111.94
223	55.1	25.31	112.75
224	54.3	25.51	113.57
225	54.1	25.71	114.38
226	54.1	25.91	115.2
227	52.9	26.11	116.02
228	52.3	26.31	116.83
229	52.9	26.5	117.65
230	52.5	26.7	118.47
231	51.1	26.89	119.28
232	50.7	27.08	120.1
233	51.1	27.27	120.91
234	49.9	27.46	121.73

235	49.3	27.65	122.55
236	49.5	27.83	123.36
237	49.5	28.01	124.18
238	47.7	28.2	125
239	47.7	28.38	125.81
240	47.7	28.55	126.63
241	46.7	28.73	127.45
242	47.1	28.9	128.26
243	46.5	29.08	129.08
244	46.1	29.25	129.89
245	45.5	29.41	130.71
246	45.7	29.58	131.53
247	45.5	29.74	132.34
248	45.5	29.91	133.16
249	44.7	30.06	133.98
250	45.5	30.22	134.79
251	45.5	30.38	135.61
252	45.1	30.53	136.43
253	44.7	30.68	137.24
254	44.9	30.83	138.06
255	43.9	30.98	138.87
256	44.1	31.12	139.69
257	44.3	31.26	140.51
258	43.5	31.4	141.32
259	43.5	31.54	142.14
260	43.1	31.67	142.96
261	42.7	31.8	143.77
262	43.1	31.93	144.59
263	43.3	32.06	145.4
264	42.3	32.18	146.22
265	42.5	32.3	147.04
266	42.3	32.42	147.85
267	42.3	32.54	148.67
268	42.5	32.65	149.49
269	41.7	32.76	150.3
270	40.9	32.87	151.12
271	41.7	32.97	151.94
272	41.7	33.07	152.75
273	40.7	33.17	153.57
274	40.7	33.27	154.38
275	40.3	33.36	155.2
276	41.3	33.46	156.02
277	40.5	33.54	156.83
278	40.1	33.63	157.65
279	39.1	33.71	158.47
280	39.3	33.79	159.28
281	38.9	33.87	160.1
282	38.9	33.94	160.91
283	38.5	34.01	161.73
284	38.5	34.08	162.55
285	37.7	34.14	163.36

286	38.5	34.21	164.18
287	37.7	34.26	165
288	36.9	34.32	165.81
289	36.9	34.37	166.63
290	36.5	34.42	167.45
291	36.9	34.47	168.26
292	36.3	34.51	169.08
293	36.1	34.55	169.89
294	36.1	34.59	170.71
295	34.5	34.62	171.53
296	34.9	34.65	172.34
297	34.1	34.68	173.16
298	34.1	34.71	173.98
299	33.5	34.73	174.79
300	33.1	34.75	175.61
301	31.9	34.76	176.43
302	32.3	34.77	177.24
303	32.3	34.78	178.06
304	31.5	34.79	178.87
305	30.9	34.79	179.69
306	30.9	34.79	180.51
307	29.7	34.79	181.32
308	30.1	34.78	182.14
309	29.9	34.77	182.96
310	29.5	34.76	183.77
311	28.7	34.74	184.59
312	29.3	34.72	185.4
313	28.3	34.7	186.22
314	28.3	34.67	187.04
315	28.1	34.65	187.85
316	27.7	34.61	188.67
317	26.9	34.58	189.49
318	26.9	34.54	190.3
319	25.7	34.5	191.12
320	26.7	34.46	191.94
321	25.7	34.41	192.75
322	24.9	34.36	193.57
323	24.5	34.31	194.38
324	24.3	34.25	195.2
325	24.7	34.19	196.02
326	24.1	34.13	196.83
327	24.1	34.06	197.65
328	22.9	33.99	198.47
329	22.9	33.92	199.28
330	22.9	33.85	200.1
331	21.7	33.77	200.91
332	22.9	33.69	201.73
333	22.7	33.61	202.55
334	22.5	33.52	203.36
335	22.5	33.43	204.18
336	21.5	33.34	205

337	22.5	33.25	205.81
338	21.7	33.15	206.63
339	21.3	33.05	207.45
340	22.5	32.95	208.26
341	21.5	32.84	209.08
342	21.7	32.73	209.89
343	20.7	32.62	210.71
344	21.1	32.51	211.53
345	21.3	32.39	212.34
346	20.9	32.27	213.16
347	21.5	32.15	213.98
348	20.9	32.03	214.79
349	21.3	31.9	215.61
350	21.1	31.77	216.43
351	20.7	31.64	217.24
352	20.9	31.5	218.06
353	21.1	31.37	218.87
354	20.3	31.23	219.69
355	20.9	31.08	220.51
356	21.1	30.94	221.32
357	20.1	30.79	222.14
358	20.5	30.64	222.96
359	20.3	30.49	223.77
360	20.7	30.34	224.59
361	20.7	30.18	225.4
362	20.1	30.03	226.22
363	19.3	29.87	227.04
364	19.3	29.7	227.85
365	20.3	29.54	228.67
366	19.7	29.37	229.49
367	19.7	29.2	230.3
368	20.1	29.03	231.12
369	19.3	28.86	231.94
370	18.9	28.69	232.75
371	19.9	28.51	233.57
372	18.9	28.33	234.38
373	19.9	28.15	235.2
374	19.1	27.97	236.02
375	19.3	27.79	236.83
376	18.3	27.6	237.65
377	18.9	27.42	238.47
378	19.3	27.23	239.28
379	18.9	27.04	240.1
380	18.7	26.84	240.91
381	19.3	26.65	241.73
382	19.3	26.46	242.55
383	18.7	26.26	243.36
384	18.9	26.06	244.18
385	19.3	25.86	245
386	19.1	25.66	245.81
387	19.7	25.46	246.63

388	18.5	25.26	247.45
389	19.5	25.05	248.26
390	19.5	24.85	249.08
391	19.7	24.64	249.89
392	19.7	24.44	250.71
393	19.9	24.23	251.53
394	19.7	24.02	252.34
395	20.3	23.81	253.16
396	20.1	23.6	253.98
397	19.9	23.38	254.79
398	20.3	23.17	255.61
399	20.3	22.96	256.43
400	19.7	22.74	257.24
401	20.7	22.53	258.06
402	20.5	22.31	258.87
403	20.3	22.1	259.69
404	20.3	21.88	260.51
405	20.5	21.66	261.32
406	20.5	21.44	262.14
407	21.1	21.22	262.96
408	20.9	21.01	263.77
409	20.9	20.79	264.59
410	21.7	20.57	265.4
411	21.5	20.35	266.22
412	20.9	20.13	267.04
413	20.7	19.91	267.85
414	20.3	19.69	268.67
415	21.3	19.47	269.49
416	21.3	19.25	270.3
417	20.9	19.03	271.12
418	22.1	18.81	271.94
419	21.7	18.59	272.75
420	21.3	18.37	273.57
421	21.7	18.15	274.38
422	21.5	17.93	275.2
423	21.3	17.71	276.02
424	21.7	17.49	276.83
425	21.7	17.27	277.65
426	21.5	17.05	278.47
427	21.7	16.83	279.28
428	22.9	16.62	280.1
429	22.1	16.4	280.91
430	22.5	16.18	281.73
431	22.5	15.97	282.55
432	21.7	15.75	283.36
433	22.1	15.54	284.18
434	22.3	15.33	285
435	22.1	15.11	285.81
436	22.5	14.9	286.63
437	22.9	14.69	287.45
438	22.7	14.48	288.26

439	23.3	14.27	289.08
440	22.7	14.07	289.89
441	23.1	13.86	290.71
442	23.1	13.65	291.53
443	23.5	13.45	292.34
444	24.3	13.25	293.16
445	24.9	13.04	293.98
446	23.9	12.84	294.79
447	24.1	12.64	295.61
448	24.3	12.45	296.43
449	23.9	12.25	297.24
450	24.5	12.06	298.06
451	23.9	11.86	298.87
452	24.5	11.67	299.69
453	24.5	11.48	300.51
454	24.5	11.29	301.32
455	24.5	11.1	302.14
456	24.5	10.92	302.96
457	24.3	10.73	303.77
458	24.5	10.55	304.59
459	23.7	10.37	305.4
460	23.5	10.19	306.22
461	24.9	10.01	307.04
462	24.5	9.84	307.85
463	24.1	9.67	308.67
464	24.5	9.5	309.49
465	24.3	9.33	310.3
466	23.9	9.16	311.12
467	24.7	8.99	311.94
468	24.1	8.83	312.75
469	23.9	8.67	313.57
470	24.1	8.51	314.38
471	23.5	8.36	315.2
472	23.3	8.2	316.02
473	23.9	8.05	316.83
474	23.7	7.9	317.65
475	23.7	7.75	318.47
476	23.3	7.61	319.28
477	23.5	7.47	320.1
478	23.5	7.33	320.91
479	23.5	7.19	321.73
480	22.9	7.05	322.55
481	23.3	6.92	323.36
482	21.5	6.79	324.18
483	22.3	6.66	325
484	21.7	6.54	325.81
485	21.9	6.41	326.63
486	21.7	6.3	327.45
487	21.5	6.18	328.26
488	22.5	6.06	329.08
489	21.5	5.95	329.89

490	21.5	5.84	330.71
491	21.3	5.74	331.53
492	21.1	5.63	332.34
493	21.3	5.53	333.15
494	21.1	5.43	333.98
495	20.7	5.34	334.79
496	20.9	5.25	335.61
497	21.1	5.16	336.43
498	20.9	5.07	337.24
499	21.1	4.99	338.06
500	20.7	4.9	338.87
501	21.1	4.83	339.69
502	20.9	4.75	340.51
503	20.5	4.68	341.32
504	21.1	4.61	342.14
505	21.1	4.54	342.96
506	20.5	4.48	343.77
507	20.7	4.42	344.59
508	20.5	4.36	345.4
509	20.7	4.31	346.22
510	20.3	4.26	347.04
511	20.3	4.21	347.85
512	20.5	4.17	348.67
513	20.9	4.13	349.49
514	20.7	4.09	350.3
515	20.5	4.05	351.12
516	20.5	4.02	351.94
517	20.9	3.99	352.75
518	20.5	3.96	353.57
519	19.9	3.94	354.38
520	19.9	3.92	355.2
521	20.7	3.9	356.02
522	20.5	3.89	356.83
523	19.9	3.88	357.65
524	19.9	3.87	358.47
525	20.3	3.87	359.28
526	20.5	3.87	.1
527	19.5	3.87	.91
528	20.3	3.87	1.73
529	19.3	3.88	2.55
530	19.9	3.89	3.36
531	19.1	3.91	4.18
532	19.1	3.92	5
533	19.9	3.95	5.81
534	19.3	3.97	6.63
535	19.7	4	7.45
536	19.5	4.03	8.26
537	19.1	4.06	9.08
538	19.3	4.1	9.89
539	19.5	4.14	10.71
540	19.5	4.18	11.53

541	19.5	4.22	12.34
542	19.5	4.27	13.16
543	19.1	4.32	13.98
544	19.1	4.38	14.79
545	18.7	4.44	15.61
546	19.5	4.5	16.43
547	19.5	4.56	17.24
548	18.3	4.63	18.06
549	19.5	4.7	18.87
550	19.3	4.77	19.69
551	18.9	4.85	20.51
552	18.9	4.92	21.32
553	19.7	5.01	22.14
554	18.5	5.09	22.96
555	19.9	5.18	23.77
556	19.5	5.27	24.59
557	20.1	5.36	25.4
558	19.3	5.46	26.22
559	19.7	5.56	27.04
560	19.3	5.66	27.85
561	19.1	5.76	28.67
562	19.3	5.87	29.49
563	18.7	5.98	30.3
564	18.9	6.09	31.12
565	19.1	6.21	31.94
566	18.1	6.32	32.75
567	18.3	6.44	33.57
568	19.3	6.57	34.38
569	18.9	6.69	35.2
570	18.3	6.82	36.02
571	19.1	6.95	36.83
572	17.1	7.09	37.65
573	18.3	7.22	38.47
574	18.1	7.36	39.28
575	18.1	7.5	40.1
576	17.3	7.64	40.91
577	18.1	7.79	41.73
578	17.9	7.94	42.55
579	17.7	8.09	43.36
580	17.7	8.24	44.18
581	17.5	8.39	45
582	17.3	8.55	45.81
583	17.1	8.71	46.63
584	17.1	8.87	47.45
585	17.3	9.03	48.26
586	17.1	9.2	49.08
587	17.1	9.37	49.89
588	17.7	9.54	50.71
589	16.7	9.71	51.53
590	16.9	9.88	52.34
591	17.1	10.06	53.16

592	16.7	10.23	53.98
593	16.9	10.41	54.79
594	16.7	10.59	55.61
595	17.1	10.78	56.43
596	16.9	10.96	57.24
597	16.3	11.15	58.06
598	17.1	11.34	58.87
599	16.7	11.52	59.69
600	16.5	11.72	60.51
601	16.3	11.91	61.32
602	15.9	12.1	62.14
603	16.5	12.3	62.96
604	16.5	12.49	63.77
605	16.3	12.69	64.59
606	16.5	12.89	65.4
607	15.9	13.09	66.22
608	16.1	13.3	67.04
609	16.5	13.5	67.85
610	16.1	13.7	68.67
611	15.7	13.91	69.49
612	15.9	14.12	70.3
613	16.3	14.32	71.12
614	16.1	14.53	71.94
615	16.1	14.74	72.75
616	15.9	14.95	73.57
617	15.5	15.17	74.38
618	15.7	15.38	75.2
619	16.1	15.59	76.02
620	15.5	15.81	76.83
621	16.3	16.02	77.65
622	15.7	16.24	78.47
623	15.9	16.45	79.28
624	16.3	16.67	80.1
625	16.1	16.89	80.91
626	16.1	17.1	81.73
627	15.5	17.32	82.55
628	15.9	17.54	83.36
629	15.9	17.76	84.18
630	15.7	17.98	85
631	15.3	18.2	85.81
632	16.5	18.42	86.63
633	15.1	18.64	87.45
634	15.9	18.86	88.26
635	14.9	19.08	89.08
636	15.9	19.3	89.89
637	15.3	19.52	90.71
638	14.7	19.74	91.53
639	14.7	19.96	92.34
640	14.7	20.18	93.16
641	15.5	20.4	93.98
642	15.3	20.62	94.79

643	15.1	20.84	95.61
644	14.9	21.06	96.43
645	15.3	21.28	97.24
646	15.3	21.5	98.06
647	14.5	21.71	98.87
648	14.7	21.93	99.69
649	14.3	22.15	100.51
650	14.7	22.36	101.32
651	14.1	22.58	102.14
652	14.7	22.79	102.96
653	14.7	23.01	103.77
654	14.5	23.22	104.59
655	13.9	23.44	105.4
656	15.3	23.65	106.22
657	14.9	23.86	107.04
658	13.5	24.07	107.85
659	13.9	24.28	108.67
660	13.9	24.49	109.49
661	14.5	24.69	110.3
662	13.7	24.9	111.12
663	13.5	25.1	111.94
664	15.1	25.31	112.75
665	13.5	25.51	113.57
666	14.1	25.71	114.38
667	14.1	25.91	115.2
668	14.5	26.11	116.02
669	13.5	26.31	116.83
670	14.9	26.5	117.65
671	15.1	26.7	118.47
672	14.9	26.89	119.28
673	15.1	27.08	120.1
674	14.5	27.27	120.91
675	14.3	27.46	121.73
676	13.7	27.65	122.55
677	14.1	27.83	123.36
678	14.5	28.01	124.18
679	15.1	28.2	125
680	14.9	28.38	125.81
681	14.9	28.55	126.63
682	14.3	28.73	127.45
683	13.7	28.9	128.26
684	14.1	29.08	129.08
685	13.9	29.25	129.89
686	14.7	29.41	130.71
687	14.7	29.58	131.53
688	13.9	29.74	132.34
689	13.9	29.91	133.16
690	14.3	30.06	133.98
691	13.3	30.22	134.79
692	13.7	30.38	135.61
693	14.1	30.53	136.43

694	14.3	30.68	137.24
695	14.3	30.83	138.06
696	13.9	30.98	138.87
697	14.1	31.12	139.69
698	13.7	31.26	140.51
699	14.3	31.4	141.32
700	13.3	31.54	142.14
701	14.3	31.67	142.96
702	13.9	31.8	143.77
703	13.9	31.93	144.59
704	14.3	32.06	145.4
705	13.5	32.18	146.22
706	13.3	32.3	147.04
707	13.9	32.42	147.85
708	13.9	32.54	148.67
709	13.5	32.65	149.49
710	13.9	32.76	150.3
711	13.5	32.87	151.12
712	13.9	32.97	151.94
713	13.7	33.07	152.75
714	13.9	33.17	153.57
715	14.3	33.27	154.38
716	14.1	33.36	155.2
717	13.1	33.46	156.02
718	14.3	33.54	156.83
719	14.1	33.63	157.65
720	14.5	33.71	158.47
721	13.7	33.79	159.28
722	13.9	33.87	160.1
723	15.3	33.94	160.91
724	14.7	34.01	161.73
725	14.3	34.08	162.55
726	15.5	34.14	163.36
727	14.7	34.21	164.18
728	15.1	34.26	165
729	15.3	34.32	165.81
730	13.7	34.37	166.63
731	13.9	34.42	167.45
732	14.7	34.47	168.26
733	15.5	34.51	169.08
734	13.9	34.55	169.89
735	14.9	34.59	170.71
736	14.7	34.62	171.53
737	15.1	34.65	172.34
738	14.5	34.68	173.16
739	15.1	34.71	173.98
740	14.7	34.73	174.79
741	13.9	34.75	175.61
742	14.5	34.76	176.43
743	15.5	34.77	177.24
744	14.7	34.78	178.06

745	14.7	34.79	178.87
746	14.7	34.79	179.69
747	15.1	34.79	180.51
748	14.1	34.79	181.32
749	15.3	34.78	182.14
750	14.9	34.77	182.96
751	14.9	34.76	183.77
752	15.7	34.74	184.59
753	14.9	34.72	185.4
754	14.7	34.7	186.22
755	14.9	34.67	187.04
756	14.5	34.65	187.85
757	14.7	34.61	188.67
758	15.1	34.58	189.49
759	14.9	34.54	190.3
760	14.3	34.5	191.12
761	14.5	34.46	191.94
762	15.3	34.41	192.75
763	14.7	34.36	193.57
764	15.9	34.31	194.38
765	15.1	34.25	195.2
766	15.3	34.19	196.02
767	14.5	34.13	196.83
768	15.5	34.06	197.65
769	15.1	33.99	198.47
770	15.5	33.92	199.28
771	15.1	33.85	200.1
772	14.7	33.77	200.91
773	15.5	33.69	201.73
774	15.3	33.61	202.55
775	15.3	33.52	203.36
776	15.3	33.43	204.18
777	15.3	33.34	205
778	15.3	33.25	205.81
779	15.3	33.15	206.63
780	15.5	33.05	207.45
781	16.1	32.95	208.26
782	16.3	32.84	209.08
783	15.5	32.73	209.89
784	16.3	32.62	210.71
785	15.3	32.51	211.53
786	16.1	32.39	212.34
787	15.9	32.27	213.16
788	16.3	32.15	213.98
789	16.3	32.03	214.79
790	16.3	31.9	215.61
791	15.7	31.77	216.43
792	16.5	31.64	217.24
793	16.5	31.5	218.06
794	16.1	31.37	218.87
795	15.7	31.23	219.69

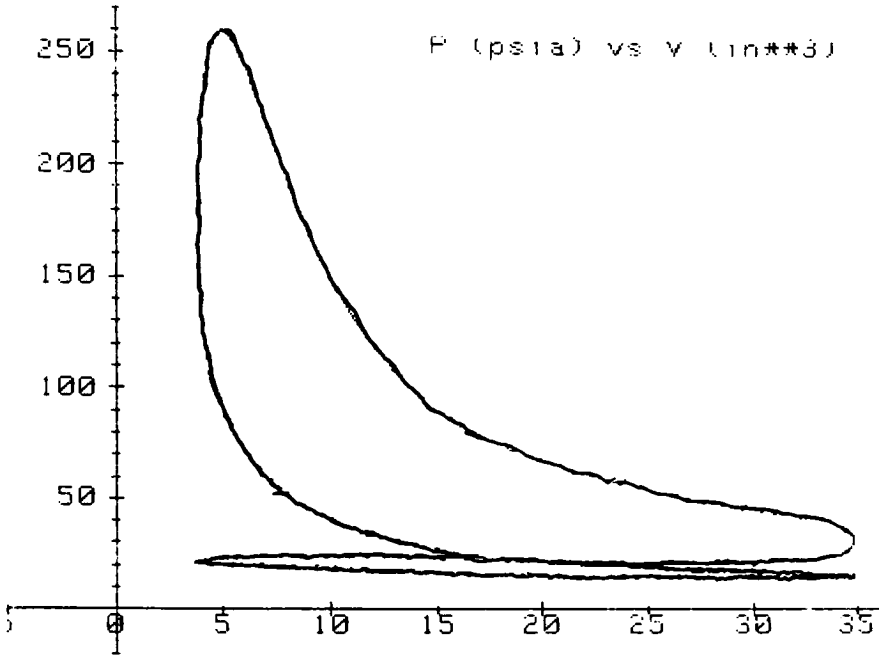
796	16.1	31.08	220.51
797	15.9	30.94	221.32
798	16.5	30.79	222.14
799	16.1	30.64	222.96
800	16.3	30.49	223.77
801	16.5	30.34	224.59
802	16.9	30.18	225.4
803	15.9	30.03	226.22
804	15.9	29.87	227.04
805	15.9	29.7	227.85
806	16.9	29.54	228.67
807	16.5	29.37	229.49
808	16.3	29.2	230.3
809	16.7	29.03	231.12
810	15.9	28.86	231.94
811	16.9	28.69	232.75
812	16.5	28.51	233.57
813	16.9	28.33	234.38
814	16.7	28.15	235.2
815	16.7	27.97	236.02
816	16.9	27.79	236.83
817	16.3	27.6	237.65
818	16.7	27.42	238.47
819	16.5	27.23	239.28
820	16.9	27.04	240.1
821	17.1	26.84	240.91
822	16.3	26.65	241.73
823	17.1	26.46	242.55
824	16.7	26.26	243.36
825	17.1	26.06	244.18
826	16.9	25.86	245
827	17.5	25.66	245.81
828	16.9	25.46	246.63
829	17.3	25.26	247.45
830	17.9	25.05	248.26
831	17.3	24.85	249.08
832	17.9	24.64	249.89
833	17.9	24.44	250.71
834	17.5	24.23	251.53
835	18.5	24.02	252.34
836	17.7	23.81	253.16
837	18.7	23.6	253.98
838	18.5	23.38	254.79
839	19.3	23.17	255.61
840	19.5	22.96	256.43
841	18.5	22.74	257.24
842	18.7	22.53	258.06
843	19.9	22.31	258.87
844	19.5	22.1	259.69
845	19.9	21.88	260.51
846	19.3	21.66	261.32

847	19.7	21.44	262.14
848	20.1	21.22	262.96
849	19.7	21.01	263.77
850	19.9	20.79	264.59
851	20.1	20.57	265.4
852	20.1	20.35	266.22
853	20.1	20.13	267.04
854	20.7	19.91	267.85
855	20.5	19.69	268.67
856	21.1	19.47	269.49
857	20.7	19.25	270.3
858	21.3	19.03	271.12
859	21.9	18.81	271.94
860	21.5	18.59	272.75
861	21.7	18.37	273.57
862	21.7	18.15	274.38
863	22.5	17.93	275.2
864	22.1	17.71	276.02
865	21.9	17.49	276.83
866	23.1	17.27	277.65
867	22.7	17.05	278.47
868	23.5	16.83	279.28
869	23.9	16.62	280.1
870	23.9	16.4	280.91
871	23.9	16.18	281.73
872	25.1	15.97	282.55
873	24.9	15.75	283.36
874	25.1	15.54	284.18
875	26.1	15.33	285
876	26.3	15.11	285.81
877	26.7	14.9	286.63
878	27.1	14.69	287.45
879	27.3	14.48	288.26
880	28.3	14.27	289.08
881	28.9	14.07	289.89
882	28.5	13.86	290.71
883	29.3	13.65	291.53
884	29.5	13.45	292.34
885	30.3	13.25	293.16
886	30.7	13.04	293.98
887	31.1	12.84	294.79
888	31.7	12.64	295.61
889	32.9	12.45	296.43
890	33.3	12.25	297.24
891	33.5	12.06	298.06
892	33.9	11.86	298.87
893	34.3	11.67	299.69
894	35.3	11.48	300.51
895	35.9	11.29	301.32
896	37.3	11.1	302.14
897	37.5	10.92	302.96_

898	38.5	10.73	303.77
899	39.3	10.55	304.59
900	39.3	10.37	305.4
901	39.9	10.19	306.22
902	40.9	10.01	307.04
903	41.3	9.84	307.85
904	42.9	9.67	308.67
905	43.3	9.5	309.49
906	44.3	9.33	310.3
907	45.5	9.16	311.12
908	46.7	8.99	311.94
909	47.1	8.83	312.75
910	48.9	8.67	313.57
911	49.5	8.51	314.38
912	50.5	8.36	315.2
913	51.5	8.2	316.02
914	51.7	8.05	316.83
915	53.9	7.9	317.65
916	54.9	7.75	318.47
917	55.9	7.61	319.28
918	57.1	7.47	320.1
919	58.5	7.33	320.91
920	60.5	7.19	321.73
921	62.1	7.05	322.55
922	62.9	6.92	323.36
923	64.3	6.79	324.18
924	66.1	6.66	325
925	67.9	6.54	325.81
926	69.3	6.41	326.63
927	69.9	6.3	327.45
928	72.1	6.18	328.26
929	73.3	6.06	329.08
930	75.5	5.95	329.89
931	77.3	5.84	330.71
932	78.9	5.74	331.53
933	80.1	5.63	332.34
934	82.5	5.53	333.16
935	83.9	5.43	333.98
936	85.5	5.34	334.79
937	88.1	5.25	335.61
938	90.9	5.16	336.43
939	92.1	5.07	337.24
940	93.7	4.99	338.06
941	96.1	4.9	338.87
942	98.5	4.83	339.69
943	100.9	4.75	340.51
944	103.1	4.68	341.32
945	105.1	4.61	342.14
946	107.7	4.54	342.96
947	109.5	4.48	343.77
948	111.9	4.42	344.59

949	113.7	4.36	345.4
950	116.3	4.31	346.22
951	119.1	4.26	347.04
952	121.5	4.21	347.85
953	123.1	4.17	348.67
954	125.5	4.13	349.49
955	127.9	4.09	350.3
956	130.5	4.05	351.12
957	133.1	4.02	351.94
958	135.3	3.99	352.75
959	137.5	3.96	353.57
960	140.3	3.94	354.38
961	143.1	3.92	355.2
962	144.7	3.9	356.02
963	148.1	3.89	356.83
964	150.7	3.88	357.65
965	153.5	3.87	358.47
966	155.9	3.87	359.28

Results Taken at 25 Degrees Spark Advance

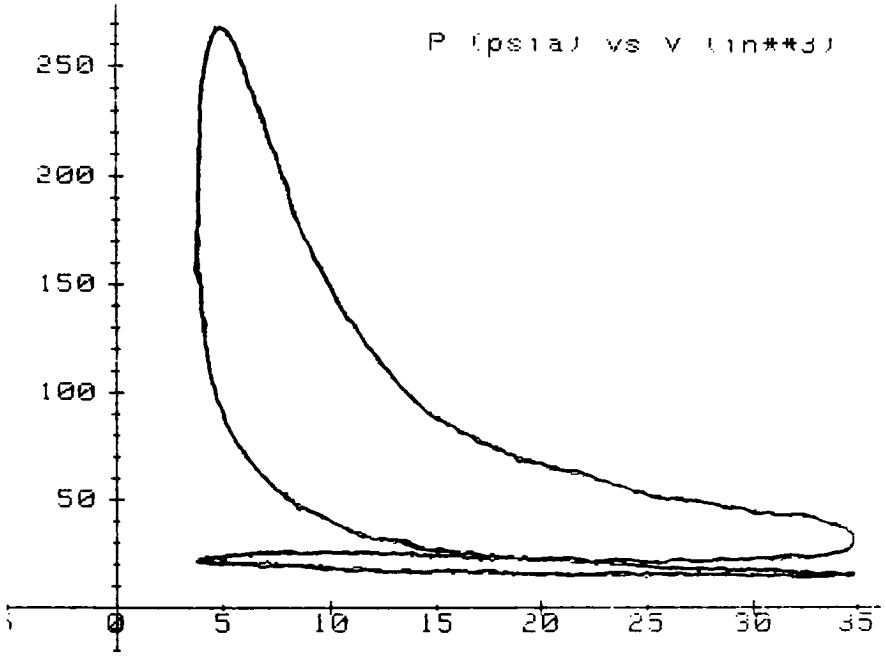


RESULTS

Engine speed:	1380.9	rpm	
Compression ratio:	9		
Work:			
Gross work output:	170.68	ft-lb	
Valve loss:	-16.46	ft-lb	
Net work:	154.21	ft-lb	
Indicated horsepower:		3.23	hp
IMEP: 66.24	psi		
Averaged over	20	cycles	

Pt.	P(psia)	V(in**3)	Angle(deg.)
115	259.5	4.88	20.82
116	259.9	4.96	21.65
117	259.3	5.04	22.48

Results Taken at 30 degrees Spark Advance

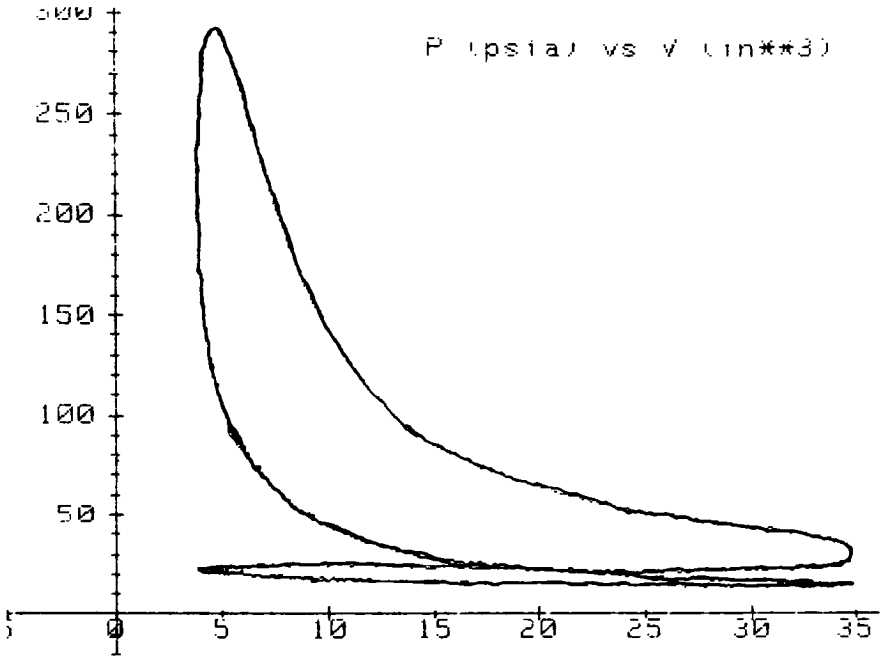


RESULTS

Engine speed:	1406.8	rpm
Compression ratio:	9	
Work:		
Gross work output:	171.02	ft-lb
Valve loss:	-17.5	ft-lb
Net work:	153.52	ft-lb
Indicated horsepower:	3.27	hp
IMEP: 66.37	psi	
Averaged over	20	cycles

Pt.	P(psia)	V(in**3)	Angle(deg.)
117	267.3	4.61	17.85
118	268.5	4.68	18.7
119	268.1	4.76	19.54
120	268.3	4.83	20.39
121	268.5	4.91	21.23

Results Taken at 35 Degrees Spark Advance

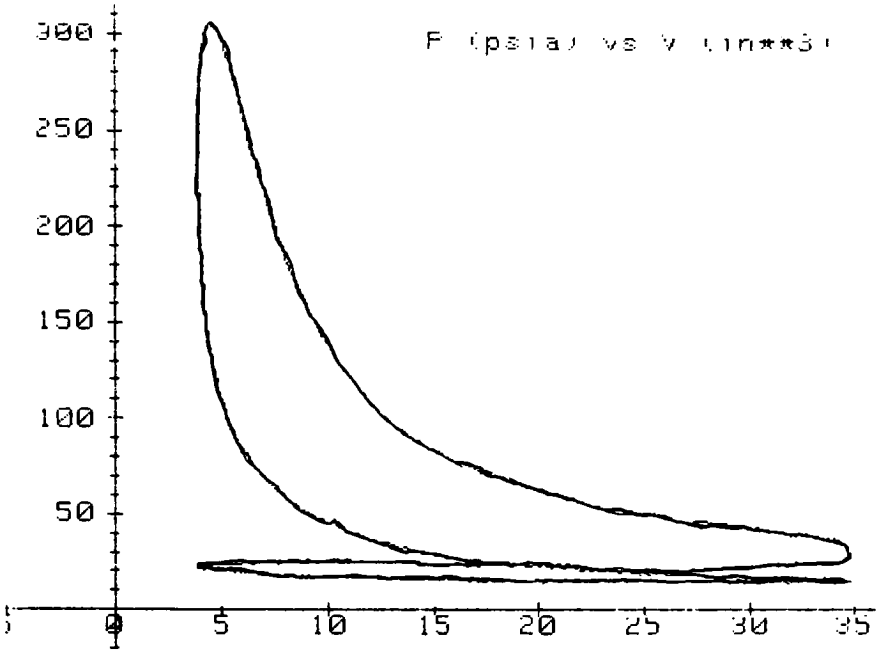


RESULTS

Engine speed:	1398.6	rpm
Compression ratio:	9	
Work:		
Gross work output:	162.36	ft-lb
Valve loss:	-18.48	ft-lb
Net work:	143.88	ft-lb
Indicated horsepower:	3.05	hp
IMEP: 63.01	psi	
Averaged over	20	cycles

Pt.	P(psia)	V(in**3)	Angle(deg.)
507	291.7	4.53	16.91
508	292.5	4.6	17.75
509	292.3	4.67	18.58

Results Taken at 40 Degrees Spark Advance

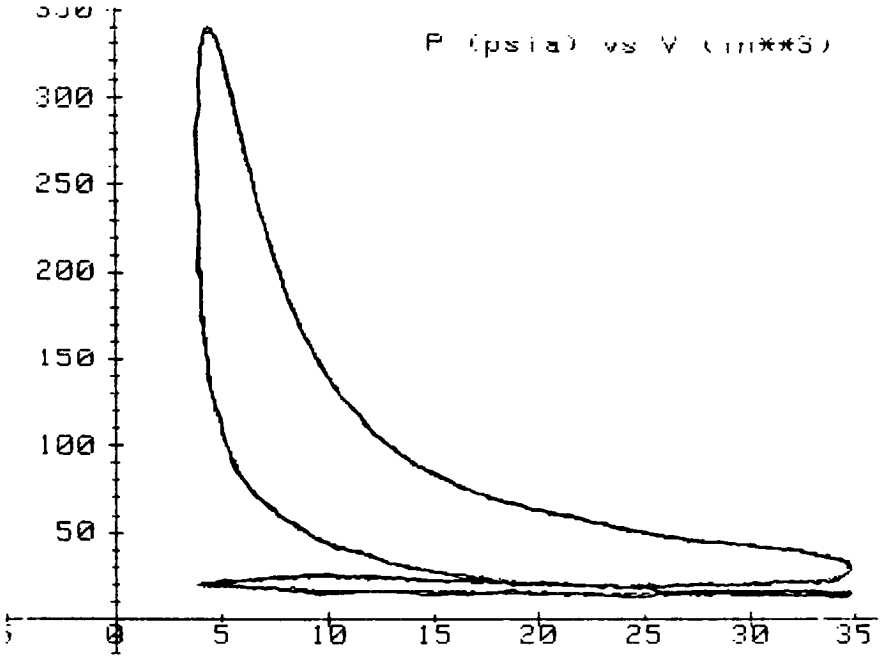


RESULTS

Engine speed:	1395.35	rpm
Compression ratio:	9	
Work:		
Gross work output:	156.69	ft-lb
Valve loss:	-18.99	ft-lb
Net work:	137.71	ft-lb
Indicated horsepower:	2.91	hp
IMEP: 60.81	psi	
Averaged over	20	cycles

Pt.	P(psia)	V(in**3)	Angle(deg.)
507	305.9	4.47	16.03
508	306.3	4.53	16.86
509	305.1	4.6	17.7

Results Taken at 45 Degrees Spark Advance



RESULTS

Engine speed:	1376.15	rpm
Compression ratio:	9	
Work:		
Gross work output:	166.67	ft-lb
Valve loss:	-15.38	ft-lb
Net work:	151.3	ft-lb
Indicated horsepower:	3.15	hp
IMEP: 64.68	psi	
Averaged over	20	cycles

Pt.	P(psia)	V(in**3)	Angle(deg.)
511	340.3	4.33	14.15
512	340.7	4.39	14.97
513	339.3	4.45	15.8

APPENDIX J

RICARDO ENGINE OPERATING INSTRUCTIONS

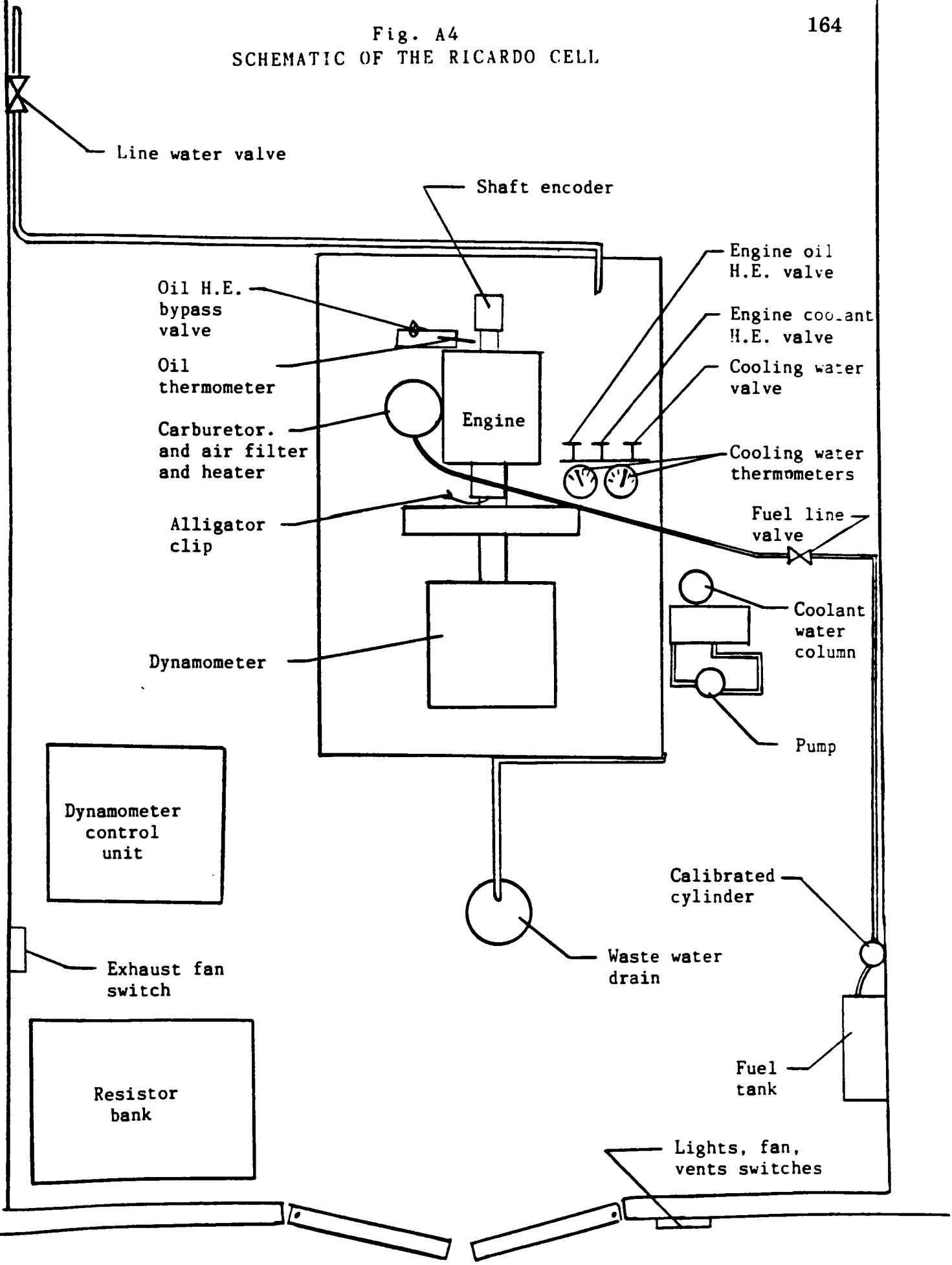
Spark Ignition Running

The following instructions lead the user through the steps in running the Ricardo Research engine in the spark ignition mode. Three figures should be referred to when using these instructions, the Schematic of the Ricardo Cell (Fig. A4), the Dynamometer Control Unit (Fig. A5), and the Ricardo Carburetor (Fig. A6). Do NOT smoke in the test cell.

STARTING THE ENGINE

1. Turn on the exhaust fan (switch on the wall in front of the dynamometer control unit) and the lights, fan and vents (switches outside the testcell door). These should remain on whenever the engine is running or has been run recently. Keep the testcell doors wide open while running the engine.
2. Check the cooling water level in the Coolant Water Column. The level should be within 8 inches of the top of the column. If it has fallen below this, add distilled water to the proper level before continuing. Plug in the water pump to the extension cord.
3. Open the Cooling Water Valve and the Cooling Water H.E. (heat exchanger) valves–these valves are open when the handles are parallel to the lines. Close the Engine Oil H.E. valve.

Fig. A4
SCHEMATIC OF THE RICARDO CELL



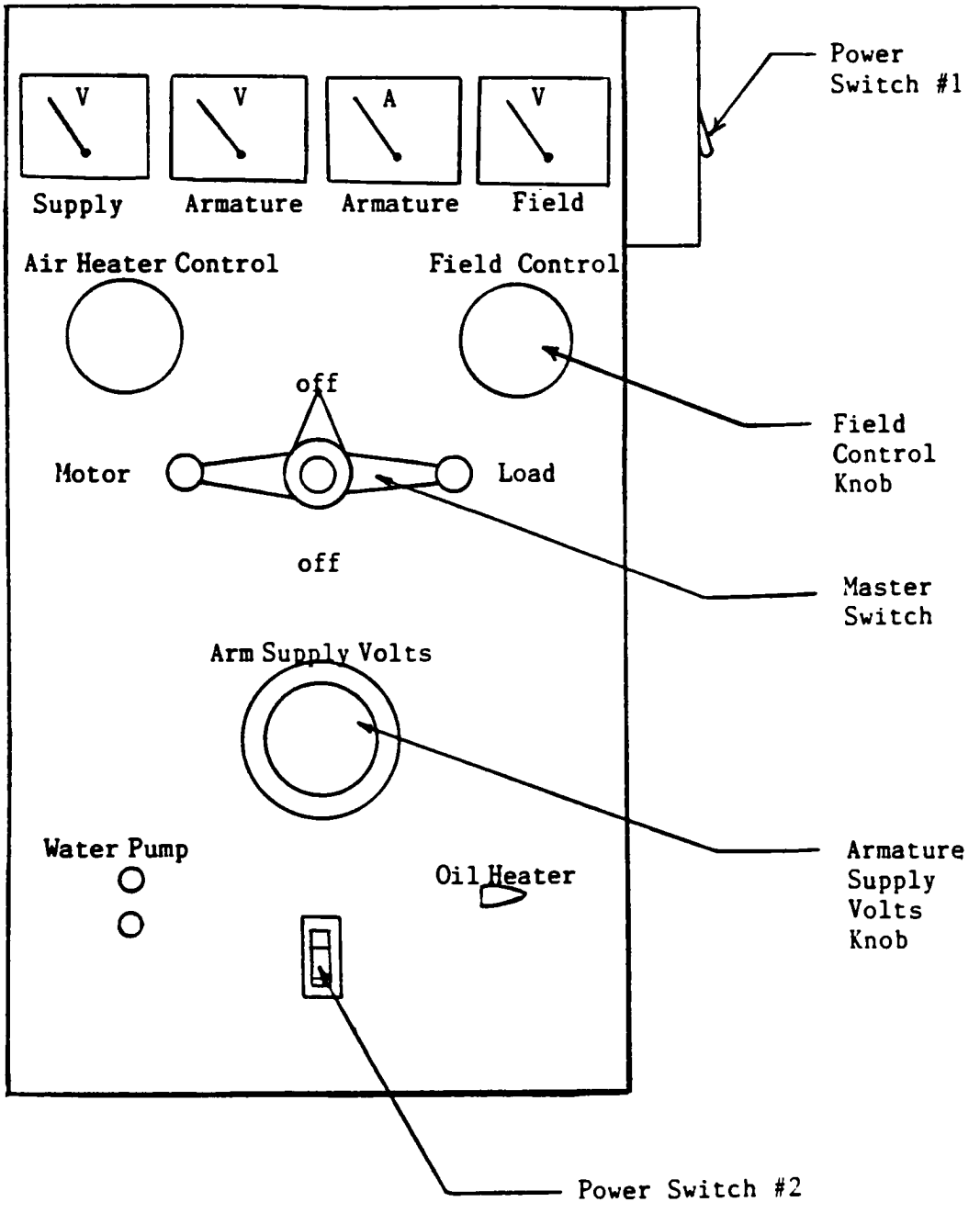


Fig. A5
DYNAMOMETER CONTROL UNIT

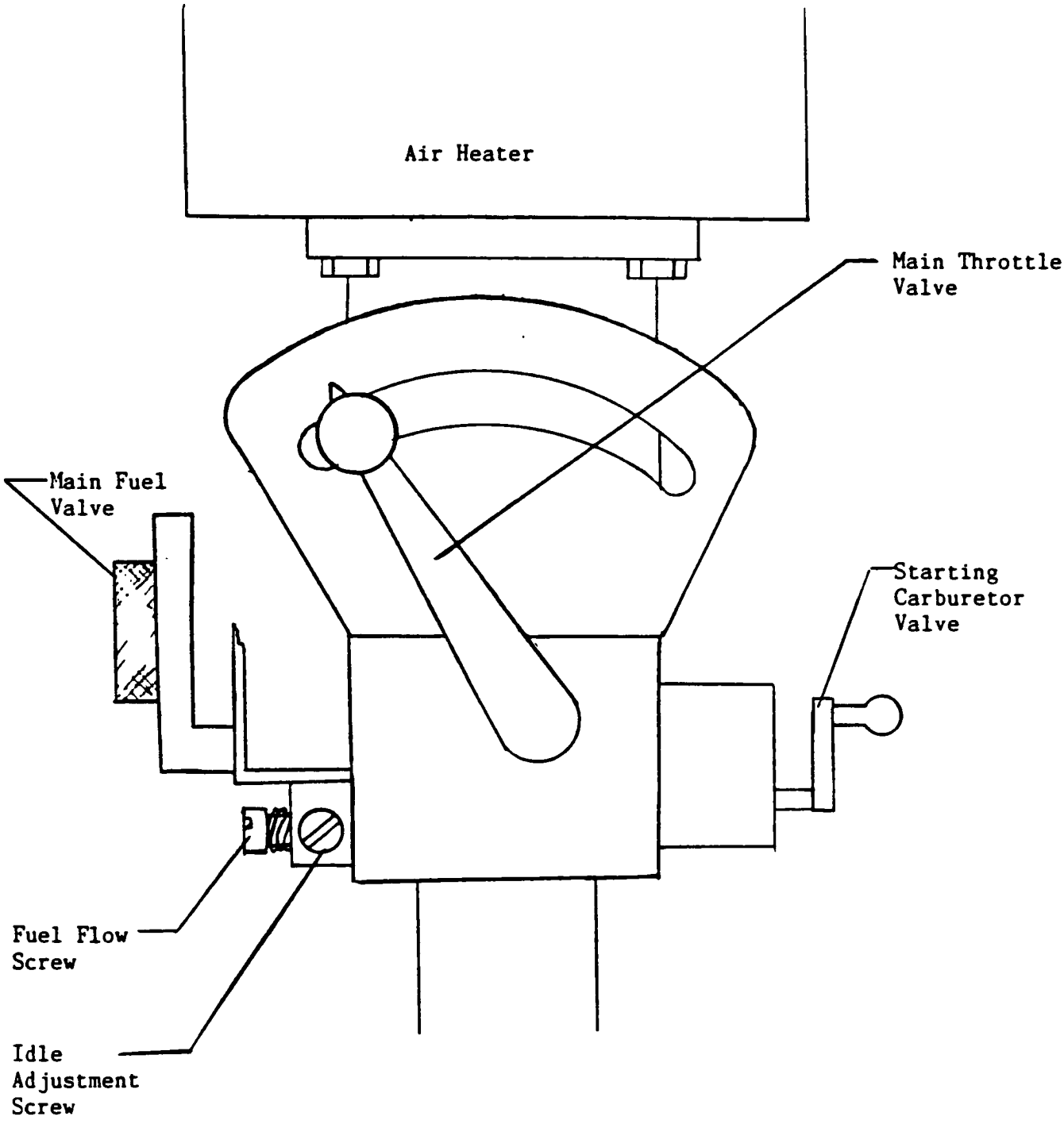


Fig. A6

RICARDO CARBURETOR

4. Open the Line Water Valve at the wall. This valve does not need to be fully open, but should be adjusted so that it runs quietly. You should now see water running down the Waste Water Drain.
5. Next, go to the carburetor, which is located under the air-filter and heating unit. Close the Main Fuel Valve fully, seating it firmly but gently. Set the Main Throttle Valve at a position about half way between the "0" and "1" marks of its scale. Make sure that the Starting Carburetor Valve is closed, the knob being fully away from you, or in its right-most position.
6. Close the Fuel Line Valve, shown in Fig. 1, near the engine. Check the two small needle valves at the "X" intersection under the Calibrated cylinder: the horizontally oriented valve should be open and the lower, vertically oriented, valve should be closed. Open the fuel line valve directly under the fuel tank. You should now see fuel entering the fuel lines and the Calibrated Cylinder.
7. Fully open the Oil H.E. Bypass Valve. This allows the lubricating oil to bypass the oil H.E. so that it can heat up faster when the engine is first running.
8. Check the settings of the control screws on the carburetor as follows. The idle adjustment screw should now be fully tightened and then backed out $1\frac{1}{2}$ turns. Fully tighten the fuel flow screw and then back it out 1 turn. While the engine is running, the main throttle valve is the only carburetor valve used to control the engine speed.
9. Make sure that the Master Switch of the Dynamometer Control Unit is in the "off" position. The Air Heater Control should be off (this can be

turned on to shorten the time it takes the engine to reach equilibrium, but it is not necessary to use it). Turn on Power Switches 1 and 2 of the Dynamometer Control Unit. Turn the Oil Heater Switch on the Control Unit to the "ON" position.

10. Use the Armature Supply Volts Knob to set the Supply Volts (the left-most gage on the Control Unit) to 60 Volts. Use the Field Control Knob to set the Field Volts (the right-most gage on the Control Unit) to the maximum possible. You are now ready to motor the engine.
11. Make sure that the alligator clip is grounded (clipped onto the screw provided) and that its wire will not interfere with the flywheel. Now turn the Master Switch on the Control Unit to the "Motor" position. The dynamometer will now act as a motor to turn the engine over.
12. Open the Fuel Line Valve.
13. Disconnect the Alligator Clip from the screw, making sure that it does not touch any other parts.
14. Put the lever on the Starting Carburetor Valve to the "OPEN" position (towards you).
15. Now comes the tricky part. After a short while, the engine will begin to fire. When you hear it begin to fire fairly regularly, turn the Master Switch of the Dynamometer to the "OFF" position. Quickly go back to the carburetor and close the Starting Carburetor Valve and turn the main fuel valve open about 1 revolution (to the 4:00 position). The engine will run for a while and then probably begin to die out. When it begins to die, open the Starting Carburetor Valve until it catches again.

This may have to be done repeatedly, until the engine is warm enough to run smoothly on the main carburetor alone.

**NOTE: If, during this part of the starting procedure, the engine begins to rev over 1,500 rpm by the tachometer on the wall and seems to be getting away form you, just SHORT OUT THE IGNITION BY CLIPPING THE ALLIGATOR CLIP TO THE SCREW. This will stop the engine very soon. Do not let the engine rev over 1,500 rpm for any length of time at this stage.

16. When the engine has run fairly smoothly for a few minutes, a moderate load should be applied. Go to the Dynamometer Control Unit and reduce the Field Volts and the Armature Supply Volts to zero (fully off). Turn the Master Switch to the "load" position. Now slowly increase the Field Volts to about 30 V. If the engine begins to die, you are probably applying the load too abruptly. Reduce the Field Volts and adjust the main carburetor until the engine runs smoothly again. The engine should be run with a moderate load of about 50 Field Volts at 1,500 rpm until the oil temperature reaches at least 60°C.

RUNNING THE ENGINE

This section consists of a list of engine operating variables that must be monitored while the engine is running and some adjustments that can be made to regulate the running of the engine. Also refer to the manual on the engine by Ricardo and Co., Engineers, Ltd.

Operating Variables to Monitor

1. **Oil Temperature:** The oil temperature should be at least 60°C before running the engine under more than a moderate load. Until this oil temperature is reached, the engine should be run at about 1500 rpm with a moderate load. To shorten the oil heating time, the electric oil heater (control on the Dynamometer Control Unit) can be turned on, and the heat exchanger bypass valve should be full open.

   To maintain the oil at a suitable operating temperature, say 60°C, the flow of the oil through the oil/water heat exchanger can be controlled using oil heat exchanger bypass valve. It can also be controlled by regulating the water flow through the heat exchanger with the Engine Oil Heat Exchanger Valve.

2. **Cooling Water Outlet Temperature:** The outlet temperature of the water circulating through the engine jacket should be maintained at about 70°C. This temperature can be monitored by the thermometer in the water outlet line. To regulate this temperature, the Engine Coolant H.E. Valve (the middle valve), can be kept partially closed. This reduces the flow of the line water through the heat exchanger and allows the water circulated through the jacket to heat up. The Cooling Water Valve can be partially closed to throttle the flow of the cooling water through the jacket, but, as a fair flowrate is required to maintain a uniform cylinder temperature, this valve should be used with moderation.

3. The Armature Volts should be kept high to keep the Armature Amps at a minimum. However, the armature Volts should not be allowed to exceed 400 Volts.

Regulating the Engine Running

The Main Throttle on the carburetor should be used to regulate the rpm of the engine. Advancing the throttle increases the rpm, and the fuel flow screw may have to be adjusted to accommodate the new throttle setting. The spark time may also have to be adjusted when the throttle setting is changed.

Turn up the Field voltage to increase the load applied by the dynamometer. Increasing the load decreases the rpm of the engine.

STOPPING THE ENGINE

1. Turn the Fuel Line Valve to the "OFF" position.
2. Short out the engine ignition by clipping the Alligator Clip to the screw.
3. When the engine flywheel is completely at rest, turn the Master Switch of the Dynamometer Control Unit to the "OFF" position. Turn off the oil heater and the air heater, if they were used. Turn off Power Switches 1 and 2 of the Control Unit.
4. Close the fuel valve under the fuel tank. Put the open end of the tubing at the "X" intersection under the Calibrated Cylinder in an appropriate can to receive the excess fuel. Open the bottom and side valves to let the fuel drain from the Calibrated Cylinder.

5. If the exit temperature of the cooling water is 70°F or less, unplug the Water Pump and turn the line water off with the Line Water Valve.
6. When you are ready to leave the room, turn off the Exhaust Fan (switch near the Dynamometer Control Unit), and the lights, fan and vents (switches outside the testcell door).

The suggestions above would increase the accuracy and depth of the analysis possible from a Ricardo engine indicator diagram. The present diagram, however, is sufficient for many purposes in engine analysis, including determination of thermal efficiency, mechanical efficiency, and evaluation of the effects of variation of engine operating conditions. It is hoped that the work represented in this report will serve to increase the value of the Ricardo engine as a research and educational tool.